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Keywords:	food waste; active phase; rapid composter; thermal composter
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First Author:	Badrus Zaman
Order of Authors:	Badrus Zaman
	Nurandani Hardyanti
	Purwono Purwono
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Abstract:	An innovative, portable thermal composter was developed to accelerate the decomposition of food waste at household. The study aimed to evaluate the performance of the composter by assessing the quality of the compost produced. Food waste was chopped, mixed, stirred at 80 rpm, and heated to ~ 55 °C; thereafter, a bulking agent and stimulated microorganisms were added to the mixture. The composter mixing speed was assessed to calculate the feasible composting time. The results revealed that the active phase of composting process could be completed in a day, producing good quality compost. The pH, electric conductivity, and C/N ratio of the compost was 6.72, 1,148–1,179 μScm-1, and 20.38, respectively. The lowest ammonia emissions (i.e., 7.2 g/Nm3) were produced on the sixth day. The total cost required to process 1 kg of food waste in a day was only 2,097.76 Indonesian Rupiah (IDR), highlighting the feasibility of this technology.

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In this study, we report that an innovative, portable thermal composter was successfully developed. This composter was used to be applied in a household level as home composting. In this study, we found that the composting process could be completed in a single day, producing high quality, mature compost. The pH, electric conductivity, and C/N ratio of the compost was 6.72, 1,148–1,179 µScm-1, and 20.38, respectively. The lowest ammonia emissions (i.e., 7.2 g/Nm3) were produced on the sixth day. Finally, the total cost required to process 1 kg of food waste in a single day was only 2,097.76 Indonesian Rupiah (IDR), highlighting the feasibility of this innovative household thermal composter. The number of words in the manuscript is 5,891 words including title page, abstract, and references.

We have no conflicts of interest to disclose. All the authors approve the contents and the submission of this manuscript to Bioresource Technology Reports Journal.

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An Innovative Thermal Composter to Accelerate Food Waste Decomposition at the Household Level

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ABSTRACT

An innovative, portable thermal composter was developed to accelerate the decomposition of food waste at household. The study aimed to evaluate the performance of the composter by assessing the quality of the compost produced. Food waste was chopped, mixed, stirred at 80 rpm, and heated to ~ 55 °C; thereafter, a bulking agent and stimulated microorganisms were added to the mixture. The composter mixing speed was assessed to calculate the feasible composting time. The results revealed that the active phase of composting process could be completed in a day, producing good quality compost. The pH, electric conductivity, and C/N ratio of the compost was 6.72, 1,148–1,179 μScm^{-1}, and 20.38, respectively. The lowest ammonia emissions (i.e., 7.2 g/Nm^3) were produced on the sixth day. The total cost required to process 1 kg of food waste in a day was only 2,097.76 Indonesian Rupiah (IDR), highlighting the feasibility of this technology.

Keywords: food waste; active phase; rapid composter; thermal composter

1. INTRODUCTION

Nearly a third of the worldwide food production for human consumption is lost or wasted, accounting for 1.3 billion tons of food per year. The high generation of food waste, representing a global economic loss, which is accounting around \$400 billion per yar (Raj et al., 2022). Among various other types of waste, food waste may generate the highest greenhouse gas (GHG) emissions, as it produces an enormous number of contaminants through natural microbial degradation and other indirect processes, including transportation and the use of food processing machinery (Shen et al., 2020). Therefore, preventing food waste at the household level, downstream of the food supply chain, is critical in limiting climate change (Parfitt et al., 2010).

There are several food waste management strategies, including composting (Cesaro et al., 2019), animal feed (Mo et al., 2018), anaerobic/aerobic digestion (Wainaina et al., 2020), gasification, incineration (You et al., 2016), pyrolysis (Kim et al., 2020), and direct landfill disposal (Goodman-Smith et al., 2020). Composting remains the most widespread solution in developing countries, where it treats ~ 90–96% of food waste (Thi et al., 2015). Effective food waste management has been proven to reduce pollutants, odors, and GHG emissions (Wei et al., 2017; Zaman et al., 2021). In addition, composting is a common practice that can be easily implemented in residential households.

Composting systems at the household and community level have been discussed by Lu and Sidortsov (2019). Household-level composting equipment allows residents to compost their food waste, ultimately reducing the volume of domestic waste transported to communal waste processing facilities. There are, however, some challenges facing composting systems at the household level. For example, there is the likelihood of odor emissions during the biodegradation process (Zhou et al., 2020). Moreover, the long processing times involved with composting may lead to residents being unwilling to compost in their homes. The success of household-level composting also depends on the knowledge, capacity, and self-awareness of the residents who manage the household's waste (Fadhullah et al., 2022).

There are some techniques presented in previous literatures for reducing the processing time of household composting. For instance, Kalamdhad et al. (2009) created a drum-shaped thermophilic composter consisting of chambers with varying temperatures at its chamber. The thermophilic conditions allow for microbial metabolism activation, accelerating the humification rate. The higher the temperature, the greater the microbiological activity will be (Ottani et al., 2022). Food waste composting with the addition of microorganisms and thermal elements (0-100 °C) reached the maximum temperature faster (3 days), and the maturation period decreased (4 weeks) (Charkhestani & Kebria, 2022). The composting time of 4 weeks is still contrary to the community's wishes, where they want the composting process to happen right after they throw the waste away in the composting machine. Awasthi et al. (2017) also found that adding multifunctional microorganisms produced better germination test results and a composting period of 20 days. A recent study reveals that adding biochar can increase the composting temperature and achieve an advanced thermophilic temperature in a short period of time. Thus, making the composting time lasted for only 20 days (Jain et al., 2018). Oktiawan et al. (2018) used a bulking agent at as much as 30% of the total waste to produce mature and stable compost. A processed food waste size of ± 2 mm is ideal for microbes to carry out the humification process and increase composting efficiency. Therefore, continuous aeration and rotation can also reduce the active phase of composting treatment from several weeks to only 4.5 days (Alkoaik, 2019). Since the processing time has become a limitation for applicability at the household level, some modifications are still required to increase its efficiency and ensure its feasibility as a household composter.

This study developed an innovative household composter with several modifications which fill research gaps and addresses issues presented in previous studies. Furthermore, the composter designed here is simple to use, portable, and operated automatically. Essentially, food waste was stirred, heated, mixed, and decomposed in the composter, allowing active phase of composting to be obtained within a short period. The aim of the study was to demonstrate the utility of a thermal composter prototype in different operational environments. Furthermore, due to the limited research and the importance for further developing food waste management strategies at the household level, the goal of this study was to demonstrate a thermal composter that may accelerate the food waste composting process. The focus here was on compost quality and morphology, ammonia (NH_3) gas emissions, and the total operating cost.

2. METHODS

This research was conducted in the greenhouse of the Environmental Engineering Department, Faculty of Engineering, Diponegoro University. The thermal composter (see Fig. 1) was made of stainless steel (Type 316 austenitic, Indonesia) with dimensions of 60 cm × 30 cm × 55 cm (length × width × height). The composter frame was made of corrosion-resistant galvalume, and its outer layer was made of white and green acrylic. The thermal composter consisted of an inlet chamber, a food waste chopper, a spiral stirrer driven by a motor (0.5 hp, 3-phase, 1370 rpm, China), and a heater (12 V). The heater was set to ~ 80 °C to accelerate the microbe metabolism and the humification rate. The bottom and sides of the composter were equipped with insulators to reduce heat loss. Finally, activated carbon and a UV lamp were attached to the top of the composter to remove odors and microorganisms resulting from the food waste decomposition (Zhou et al., 2020)

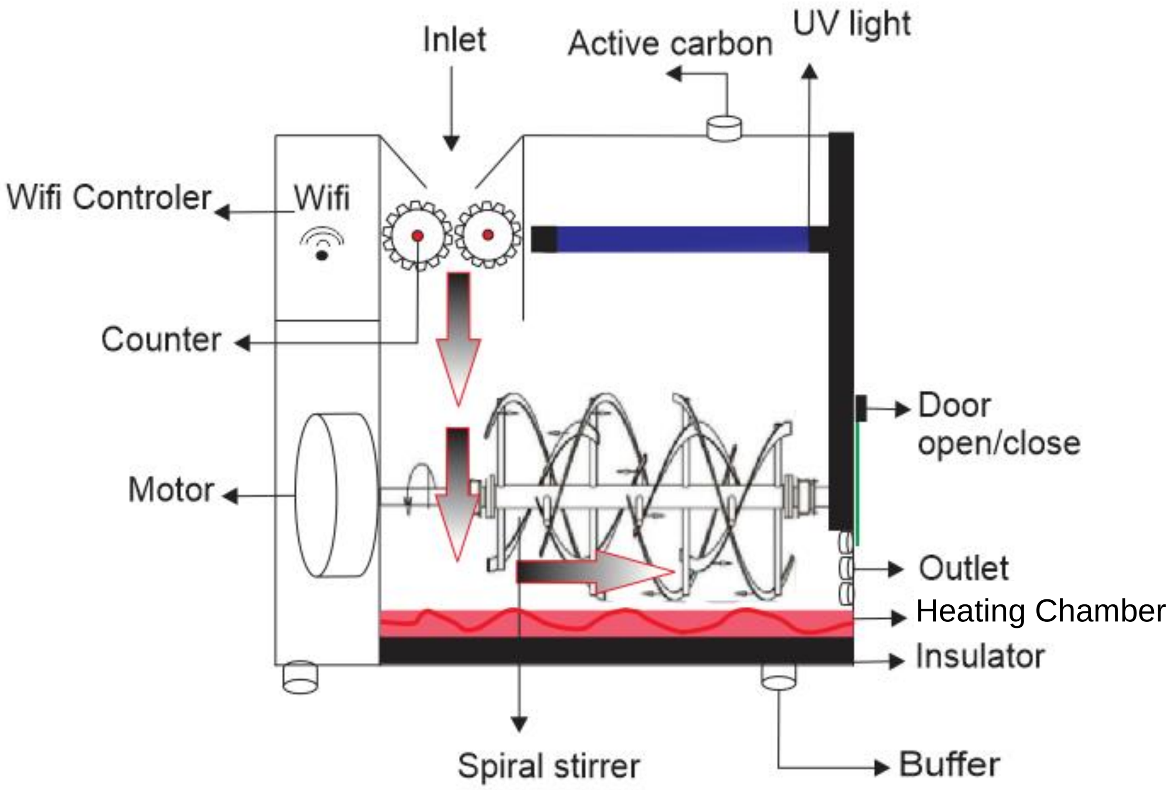


Fig. 1. Schematic diagram illustrating the design of the thermal composter developed in this study.

Food waste was collected from a restaurant in Semarang City using trash bags and transported to the Environmental Laboratory, Faculty of Engineering, Diponegoro University for analysis. Prior to starting the experiment, the composition and physical properties of the food waste were determined; thereafter, the food waste was mixed. The bulking agent used here came from mature and stable compost with a size of 100 mesh. The food waste consisted of various and mixed ingredients such as leftover rice, spinach, chayote, banana peels, vegetable gravy, and many more. First, food waste (500 g per day) was added to the composter inlet and chopped until the food waste particle size was homogenized to ~ 2 cm. Thereafter, the bulking agent was added, accounting for as much as 30% (v/v) of the total food waste. The mixture was then periodically stirred by the spiral stirrer and slowly pushed into the heating chamber, where it was rotated for 1 min every 6 h. Despite the heater being set to 80 °C, the mixture's temperature gradually decreased to 28–30 °C while in the cooling compartment or outlet chamber. The composting cycle was carried out for 7 d by adjusting the rotational speed of the spiral stirrer to 80 rpm. Compost was removed via the outlet chamber, with samples collected daily and stored at 4 °C until further analysis.

Laboratory tests were conducted to ensure that the compost was actively produced. Compost quality was assessed using the following parameters: (a) moisture content (MC), (b) electric conductivity (EC), (c) pH, (d) temperature, (e) total nitrogen (TN), and (f) total organic carbon (TOC). The gravimetric method was used to determine the MC, with the sample being heated to 105 °C using an oven (Memmert UN 50, Germany). The Kjeldahl method was used to determine TN, while TOC was assessed using the Walkley-Black method (UV-Vis 150 Spectrophotometer, Thermo Fisher Scientific, USA). The NH_3 emissions were assessed using the indophenol method and a spectrophotometer (Indonesia National Standard – SNI 19-7119.1-2005). The compost surface morphology was assessed using scanning electron microscopy (SEM) (Phenom ProX Desktop Scanning Electron Microscope, Thermo Fisher Scientific, USA) at a magnification of 100,000x. To do so, 2 g samples of three compost components (i.e., the bulking agent, food waste, and final compost) were collected and oven-dried at 110 °C for 48 h (Memmert, Germany). The sample was ground, sieved through 200 mesh and fixed on a stub (circular metallic plate holder). Thereafter, the sample was sputter coated with gold (Sputter Coater, Quorum Q300T D Plus, UK), ensuring visibility of the morphology.

Plant growth tests were conducted to assess the quality of the compost as a plant growth medium. This was done following the procedure described in Nguyen et al. (2020). Mung bean (*Vigna radiata*) plants sourced from a farm shop (Semarang, Indonesia) were planted in nine polybags of 5 cm × 15 cm (width × height) containing compost samples. All plants were treated equally and received the same daily watering. At 7 d, the plants were removed from the polybags, and several morphological parameters were measured, including height, weight, root length, and the number of leaves. The plant heights were measured using a ruler, plant weights were measured using an analytical balance (Mettler Toledo, Switzerland), and the germination rates were observed daily. The presence of flies and odors was recorded following the methodology described in Lleó et al. (2013). Finally, an economic evaluation was undertaken, aiming to assess the total costs incurred while operating the thermal composter. The total electrical power required for each component of the composter was converted into Indonesian Rupiah (IDR). Components that required electric power were the chopper, heater, spiral stirrer, and UV lamp. Replacement costs of the activated carbon and bulking agent were also calculated in detail. No labor or transportation costs were incurred.

3. RESULTS AND DISCUSSION

3.1. Moisture Content (MC)

The food waste contained an MC of 86.64% (Table 1); this was much higher than the recommended MC (i.e., 40–60%) for favorable microbial growth (Guidoni et al., 2018). However, food waste can produce a significant amount of gas and favors anaerobic processes, which in turn can produce foul odors and contribute to the emission of GHGs (Onwosi et al., 2017). The bulking agent contained an MC of 43.16% (Table 1). Despite this, during the composting process, the MC of the food waste and bulking agent mixture decreased drastically to 32.58% after 24 h (Table 1); this was due to the chopping, heating, and stirring that took place in the thermal composter. Water in the food waste evaporated during the heating and thermophilic composting process; this resulted in the MC decreasing to 19.76% at 4 d, while at 5 and 7 d, MCs increased to 23.55% and 23.89%, respectively (Table 1).

The microbes almost became inactive after the MC dropped below 20%; at this stage, the compost products could have been bagged (Zhou et al., 2020). The bulking agent, owing to its compression resistance, helped maintain the porosity and structure of the mixture during composting. Indeed, no leachate was observed, indicating that the addition of the bulking agent influenced the total amount of leachate formed during composting (Guidoni et al., 2018). Finally, the stirring frequency helped maintain the porosity of the mixture and added oxygen to the system.

Table 1. Compost quality parameters and growth test results.

Parameter	**Units**	**FW**	**BA**	**C-1**	**C-2**	**C-3**	**C-4**	**C-5**	**C-6**	**C-7**
MC	%	86.64	43.16	32.58	25.00	25.50	19.76	23.55	24.07	23.89
pH	-	6.63	6.70	6.72	6.32	6.49	6.53	6.72	6.27	7.01
EC	μScm^{-1}	1,591	3,270	891	1,148	1,124	1,435	960	1,170	1,179
Growth test										
Height	cm	0	7.8	25.3	24.8	20.8	21.7	0	18.5	12.4
Weight	g	0	0.2403	0.4512	0.5116	0.4413	0.5308	0	0.5061	0.4843
Root length	cm	0	1.5	5.2	4.5	4.4	4.2	0	2.3	1
Leaf	single leaves	0	2	2	2	2	2	0	2	2

FW, food waste; BA, bulking agent; C-1–C-7, daily composting results (i.e., 7 d).

3.2. pH and Temperature

The food waste had an original pH of 6.63, while the bulking agent had a pH of 6.70 (Table 1). The daily addition of food waste did not significantly alter the mixture's pH, with the mixture at 1 and 7 d having pHs of 6.72 and 7.01, respectively. This pH range is ideal for developing bacteria and fungi, thus, contributing to the composting process in producing high-quality and mature compost. Yuan & Zhu (2016) stated that the addition of a bulking agent accelerates the increase in pH. Typically, food waste that undergoes natural decomposition produces an acidic pH due to the formation of organic acid (Guidoni et al., 2018). The pH then begins to increase due to the ammonification of organic matter, where organic nitrogen is transformed into amide and ammoniacal nitrogen. The formation of NH_3, an alkaline reaction, also increases the pH. Zhou et al. (2020) found that processing food waste using a composter produced weakly acidic pHs during the initial and cooling stages, while an increase in pH was observed during the heating and thermophilic stages. Ultimately, the changes in pH may be attributable to pH imbalances caused by the microbial metabolic activity. Based on the pH value results, compost produced by the thermal composter could be taken during any of the seven composting process days and be used for agricultural purposes.

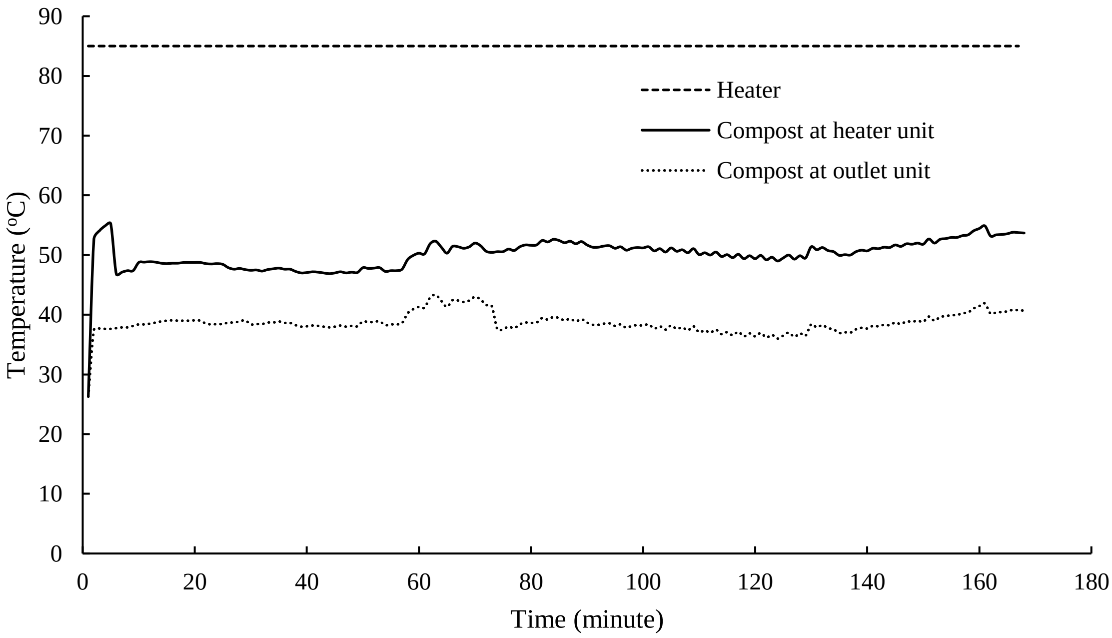


Fig. 2. Graph illustrating the temperature of the thermal composter heater (dashed line), as well as the compost temperature in the heating (solid line) and outlet chambers (dotted line).

The heater of the thermal composter was set to 80 °C, ensuring consistent thermophilic conditions in the heating chamber (Fig. 2). The composting temperature in the heating chamber rose rapidly from 26.3 °C to 52.63 °C within the first 20 min (Fig. 2). Within the same period, however, the composting temperature in the outlet chamber only rose from 26.3 °C to 37.44 °C (Fig. 2). A temperature of 52.63 °C in the heating chamber was beneficial for thermophilic microbial metabolism. At 7 d, the compost temperatures in the heating and outlet chambers were 53.69 °C and 40.69 °C, respectively (Fig. 2), indicating rapid food waste composting in the thermal composter. The thermophilic temperature positively impacts the decomposition rate of food waste so that the composting process can be completed in a day. In addition, this thermophilic temperature decreases food waste's water content, where the initial 86.64% food wastewater content decreases to 32.58% (day 1) and 23.89% (day 7).

3.3. Electric Conductivity (EC)

The original food waste and bulking agent EC values were 1,591 μScm^{-1} and 3,270 μScm^{-1}, respectively. The mixture had an EC value of 0.891 μScm^{-1} after being processed for 1 d in the thermal composter. The observed EC value decrease was due to the chopping, heating, and thermophilic decomposition that occurred in the thermal composter. However, the overall EC value during the composting process did not alter significantly and had a range of 1,148–1,179 μScm^{-1}. EC values reflect the salinity of the composting matrix (Onwosi et al., 2017). Furthermore, compost is safe for planting when it displays an EC value < 4,000 μScm^{-}

^{1}. In this study, EC values were consistently < 2,000 μScm^{-1} during the composting process, and thus, had no impact on biological activity (Mujtaba et al., 2021).

3.4. Flies and Odor

Flies typically land on food waste soon after its disposal. However, in this study, no flies were observed for 7 d, implying that the food waste and the products of its decomposition did not attract flies. Stirring of the mixture every 6 h did not affect the number of flies. A previous study found that the capacity of the composter was sufficient to stabilize the organic waste (Blazy et al., 2014). Guidoni et al. (2018) found that flies disappeared after the eleventh day of composting three treatments which varied in their ratio of rice husk to raw fruit and vegetables (i.e., 70:30, 50:50, 30:70; v:v). No strong odor was detected during this study. The bulking agent addition allowed the diffusion of gases and it maintained an aerobic composting process. In addition, bulking agents enhanced the inter-particle voids in the composite pile, thereby increasing the air permeability and regulating the humidity of the compost substrate (Yang et al., 2019).

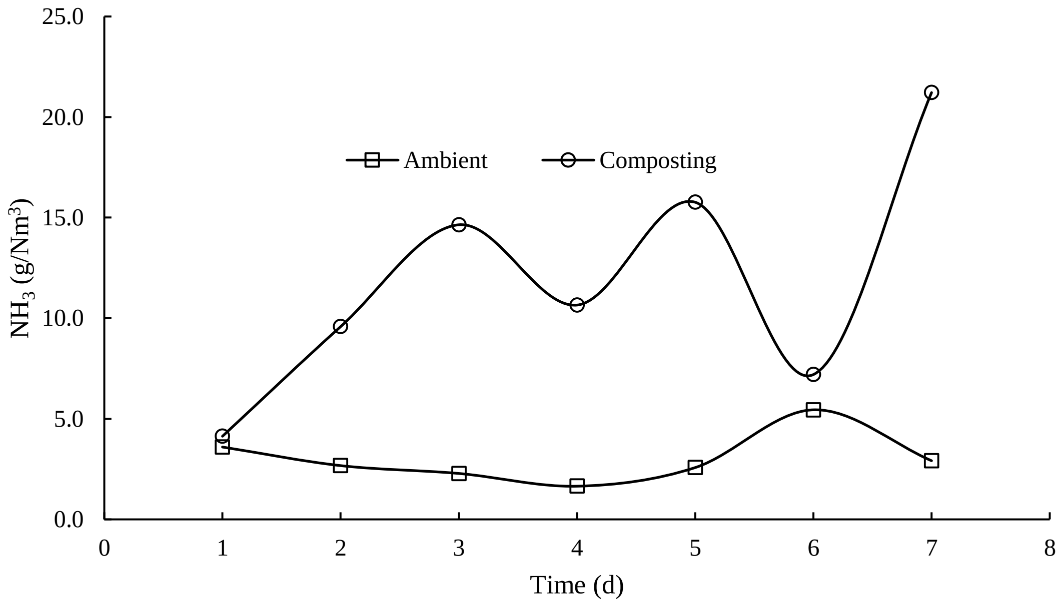


Fig. 3. Graph illustrating ammonia (NH_3) concentrations in ambient air (squares) and NH_3 emissions during seven days of composting using a thermal composter (circles).

3.5. NH_3 Emissions

Emission of NH_3 varies according to the substrate composition, particle sizes, moisture, oxygen distribution, initial temperature gradients, and the overall process conditions (Onwosi et al., 2017). The first day of the composting process produced an NH_3 emission of 4.1 g/Nm^3, with an increase to 9.6 g/Nm^3 occurring at 2 d (Fig. 3). This increase was likely due to the addition of food waste; moreover, the increasing trend continued until 7 d, which saw an NH_3 emission of 21.2 g/Nm^3 (Fig. 3). The NH_3 concentrations in ambient air ranged from 1.6–5.4 g/Nm^3, with the lowest concentration (i.e., 1.6 g/Nm^3) occurring at 4 d and the highest concentration (i.e., 5.4 g/Nm^3) at 6 d (Fig. 3). Overall, the NH_3 concentrations in ambient air did not change significantly ($p > 0.05$).

3.6. Total Organic Carbon (TOC)

Higher levels of TOC degradation indicate more stable compost (Sharma et al., 2017). After 1 d in the thermal composter, the TOC of the compost mixture decreased drastically by 75.94%. The TOC for the remaining days ranged from 77.42–79.94%, lower than the initial TOC level (See Fig. 4). The decrease observed here supports Lalremruati & Devi (2021), who stated that the decomposition of vegetable waste is straightforward, owing to it mostly containing cellulose. Liu et al. (2018) reported a decrease in vegetable waste TOC ranging from 11.4–32.1%, when using sawdust, cow dung, and inoculum for 40 d. Notably, the TOC decrease observed in this study remained stable (i.e., 77.42–79.94%) throughout the 7-d period, despite the addition of 500 g of food waste per day (Fig. 4). Indeed, these results indicate that the thermal composter is effective in accelerating the degradation of TOC, owing to the integration of the mixing system, heating parameters, and bulking agent.

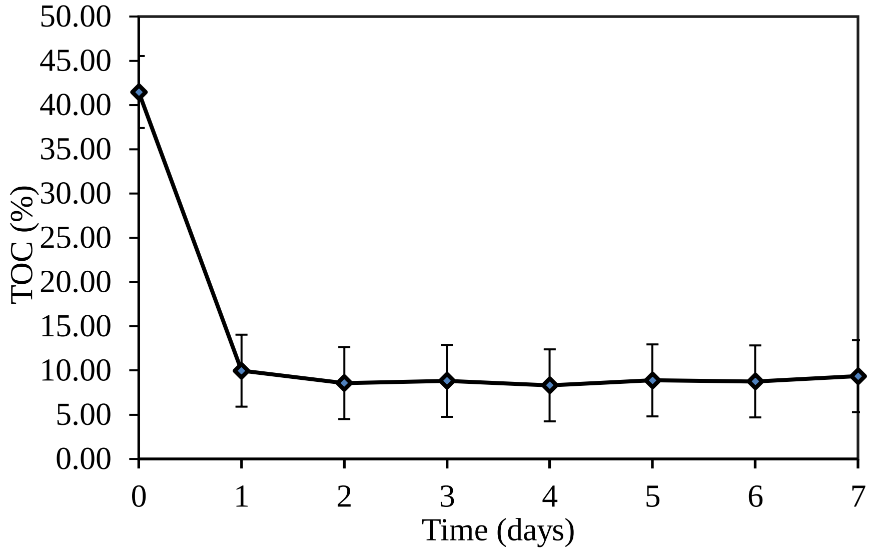


Fig. 4. Graph illustrating the level of total organic carbon (TOC) in food waste during seven days of composting using a thermal composter.

3.7. Total Nitrogen (TN)

The initial TN value decreased significantly at 2 and 3 d of the composting process. The decrease in TN is caused by the evaporation of ammonia, and lower pH results in less organic matter mineralization (Wang et al., 2017). As it may see in Fig. 3, the ammonia emission increased from 9.6 to 14.6 g/Nm^3. Therefore, the pH values for 2 and 3 d remain at 6.32 and 6.49, respectively, which are lesser than the pH at 1, 4, 5, and 7 d. Indeed, several studies have attributed the decrease in TN to the volatilization of NH_3, when temperature and pH were more than 45 °C (Cáceres et al., 2018; Zhou et al., 2018). Nguyen et al. (2020) found that TN was influenced by temperature; in addition, the optimal TN was found in experiments that were rotated once per day and exhibited a C/N ratio of 20. Regarding the production of compost from domestic organic waste (Indonesia National Standard – SNI 19-7030-2004), the optimal TN for compost is a minimum of 0.40%. Indeed, the results obtained here confirm that the TN content in the compost collected at 1, 4, 6, and 7 d meet this quality standard. The highest TN content (i.e., 0.49%) was found on the first day, while the lowest TN content (i.e., 0.28%), which does not meet the quality standard, was found at 3 d. Ultimately, temperature and the composition of the compost raw material can affect the TN in the compost.

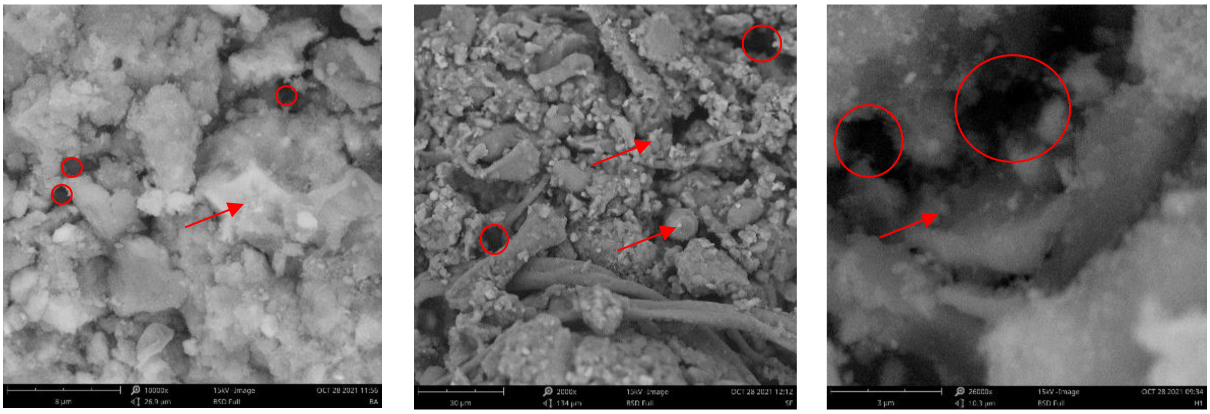
3.8. C/N Ratio

The C/N ratio is a conventional parameter used to assess the composting process (Zhou et al., 2018). The reduction of the C/N ratio due to the simultaneous consumption of carbon and nitrogen organic substrates indicates an effective composting process (Wang et al., 2016), with composts that display a C/N ratio < 20 being considered mature. According to the Ministry of Agriculture of Indonesia Number: 28/Permentan/SR.30/5/2009, organic and biological fertilizers, as well as soil enhancers, typically exhibit C/N ratios within the range of 15–25. The composting process in this study was 500 g of food waste being used as the initial compost raw material; on each of the ensuing days, an additional 500 g of food waste with a typical composition was added. The results reveal that the food waste at 2, 3, and 5 d had C/N ratios > 25, ultimately displaying poor composting conditions; whereas at 1, 4, 6, and 7 d, the C/N ratios ranged from 20–25, indicating good compositions. The C/N ratio variation found in this study was ultimately driven by differences in the daily food waste composition and quantity.

3.9. SEM Images

SEM was used as an additional technique to assess micro-changes in the surface morphology of different compost components (See Fig. 5). In SEM, a focused high-energy electron beam is used to scan the surface of a specimen (Oñiguez et al., 2011). The resulting high-quality images provide information about the sample's external morphology (texture) and crystalline structure. Micrographs of food waste samples, compost, and the bulking agent (as

provided in supplementary materials) reveal different particle sizes and distributions per unit area, as well as heterogeneity in particle compaction. Moreover, micrographs showed that the compost sample exhibited larger pore diameters and had no particle compaction. However, while the initial food waste displayed small pore diameters, particle compaction was present. Biodegradation has been shown to lead to improved texture and particle compaction (Arora & Kaur, 2019). The same result was shown by Ajmal et al. (2021), where the food waste has tightened microscopic structure compared to the compost product. This result may be due to the microorganism activity, which reduces the particle size and increase the holes of the fermented food waste. Moreover, the surface roughness and irregular pore shapes shown in the compost product may indicate the possibility of microbial degradation during the composting process (Ma et al., 2022).



(a) (b) (c)

Fig. 5. Surface morphology of (a) bulking agent, (b) food waste, and (c) compost produced from thermal composter at 10,000x magnification. The red arrows indicate the distribution of particle sizes and the circles indicate the pore diameters.

3.10. Growth test

Compost products derived from food waste generally provide improved plant growth conditions. The plant growth tests revealed rapid and consistent daily mung bean growth.

Growth tests using compost taken from six of the seven composting days (i.e., 1–4, 6, and 7 d) as well as the bulking agent alone, resulted in increased plant height and weight (Table 1). Growth tests using the fresh food waste alone, however, did not facilitate any plant growth (Table 1), with the waste beginning to rot at 1 d. Moreover, no plant growth was observed t 5 d (Table 1); this was due to the accumulation of acidic decomposition products. Ultimately, the results presented here agree with the literature that compost from food waste can be used as a plant growth medium (Nguyen et al., 2020).

3.11. Practical Evaluation and Future Research Direction

Household food waste composting does not require labor, transport, sorting, or processing fees. Zhou et al. (2020) believe that the in-situ composting system differs from the centralized composting system. The thermal composter used in this study processed 1 kg of food waste per day, using a total electrical power of 1.452 kWh. This total power consists of the shredding unit (i.e., 0.00375 kWh), the spiral stirring unit (i.e., 0.00828 kWh), and the heating unit (i.e., 1.440 kWh). To process 1 kg of food waste in a day, the heating unit required the most power as it operated for 24 h, while the shredding and stirring units operated for only 30 and 80 s, respectively. The total cost for operating the thermal composter amounted to 2,097.76 IDR to process 1 kg of food waste in a single day. The total cost of the composter developed by Zhou et al. (2020) requires $0.033 (445.98 IDR) per kg for food waste, but the composting time is longer (four days). Even though the electricity cost is 2,097.76 IDR to process 1 kg of food waste in a day, food waste composting using a thermal composter still get profits from selling the compost product as a fertilizer for 5,000.00 IDR (Paduloh & Rosihan, 2021). Moreover, the compost improves soil quality, assists the remediation of contaminated soil and reduces the need for chemical fertilizers. Solar cells can be an alternative AC power source for thermal composter operations. In addition, it is necessary to increase public acceptance of the thermal composter so that they can use it to treat food waste.

4. CONCLUSION

Thermal composting is considered a straightforward and effective strategy to manage household food waste. In this study, an innovative household thermal composter was developed and its feasibility assessed. Active phase of composting was finished after a single day of treatment, with MC, pH, temperature, EC, TOC, TN, C/N ratios, and SEM images meeting the criteria required for high quality compost. Regardless, the compost obtained after a single day was used successfully as a plant growth medium, confirming the compost's low toxicity level. Furthermore, the composter was shown to require a small amount of daily electricity to process food waste.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest exists.

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https://doi.org/10.1016/j.psep.2020.05.039.

LAMPIRAN 2

Response to Reviewer Comments

No	Comments	Response	Modification
Reviewer 1			
1)	Page 2, lines 31-34; please provide the reference for the statement "Among various other types of waste, food waste may generate the highest greenhouse gas (GHG) emissions, as it produces an enormous number of contaminants through natural microbial degradation and other indirect processes, including transportation and the use of food processing machinery."	We added the references as suggested.	Among various other types of waste, food waste may generate the highest greenhouse gas (GHG) emissions, as it produces an enormous number of contaminants through natural microbial degradation and other indirect processes, including transportation and the use of food processing machinery (Shen et al., 2020). Therefore, preventing food waste at the household level, downstream of the food supply chain, is critical in limiting climate change (Parfitt et al., 2010).
2)	Page 5, lines 103-104; there is no clear idea on why the food waste considered for composting consisted of only rice, spinach, chayote, and banana peels, whereas the food waste collected from a restaurant usually has many other items in it.	We agreed with your opinion. We realized that there is a mistake here. After careful cross checked, we modified the sentences.	The food waste consisted of various and mixed ingredients such as leftover rice, spinach, chayote, banana peels, vegetable gravy, and many more.
3)	Page 8, table 1; please check the height of the plant with bulking agent and the EC value of C-1.	The punctuation errors are revised as suggested.	Height should be 7.8 and EC value of C-1 should be 891
4)	Page 13, lines 251-254; please check the pH values for day 2 and 3 as there is loss of TN when the pH values rises above 7.7 whereas in the table 1 the pH values for day 2 and 3 remain 6.32 and 6.49 respectively, which are lesser than the pH of days 1, 4, 5 and 7.	We made a modification and added some discussion in the mentioned part of the manuscript. We hoped that the discussion can answer reviewer doubt.	The initial TN value decreased significantly at 2 and 3 d of the composting process. The decrease in TN is caused by the evaporation of ammonia, and lower pH results in less organic matter mineralization (Wang et al., 2017). As it may see in Fig. 3, the ammonia emission increased from 9.6 to 14.6 g/Nm^3. Therefore, the pH values for 2 and 3 d remain at 6.32 and 6.49, respectively, which are lesser than the pH at 1, 4, 5, and 7 d. Indeed, several studies have attributed the decrease in TN to the volatilization of NH_3, when temperature and pH were more than

No	Comments	Response	Modification
			45 °C (Cáceres et al., 2018; Zhou et al., 2018).
5)	Page 13, line 272-274; please elaborate on the different composition of the additional 500 g of food waste added to the initial compost raw material.	We want to clarify that the food waste has a typical composition since we took the food waste from the same restaurant	The composting process in this study was 500 g of food waste being used as the initial compost raw material; on each of the ensuing days, an additional 500 g of food waste with a typical composition was added.
6)	Page 15, section 3.11; the economic evaluation section can be further improved by comparing the cost analysis of the present thermal composter to that of the cost analysis of the conventional composters reported in the previous literatures.	Because there is a limitation regarding number of table and figure, we don't add any tables/figures. We added more discussion to answer the suggestion of reviewer. The economic evaluation is improved by comparing the composter developed by Zhou et al. (2020) with the current study.	The total cost of the composter developed by Zhou et al. (2020) requires \$0.033 (445.98 IDR) per kg for food waste, but the composting time is longer (four days). Even though the electricity cost is 2,097.76 IDR to process 1 kg of food waste in a single day, food waste composting using a thermal composter still get profits from selling the compost product as a fertilizer for 5,000 IDR (Paduloh & Rosihan, 2021).
7)	I think the format of citations and referencing are not following the styles needed by this journal. Please check the guidelines.	Thank you for your suggestion. In the revised manuscript, we followed journal guidelines here: https://www.elsevier.com/journals/bioresource-technology-reports/2589-014X/guide-for-authors. The changes indicated in red colour.	Included in the manuscript
8)	The typo-errors need to be taken care of throughout the manuscript.	The typo errors are already checked line by line.	Table 1: 7,8 modified to 7.8 0,891 modified to 891
Reviewer 2			
1)	The presented MS entitled "An Innovative Thermal Composter to Accelerate Food Waste Decomposition at the Household Level" may be an interesting read to scientific community for food waste valorization. However, the indepth read of the MS	Thank you for your suggestion. The gaps analysis of the manuscript in the introduction section has been improved. The discussion also modified to support the novelty of this study.	-

No	Comments	Response	Modification
	showed that MS requires a major critical revision prior to reconsideration for this journal. In general, the research results provided are not well supported with proper discussion. Besides, the author should emphasis he novelty of the statement.		
2)	Abstract needs to be redraw, which summarizes the overall research work and major findings in graphical form. The authors should follow the general's guideline for more information https://www.elsevier.com/journals/bioresource-technology-reports/2589-014x/guide-for-authors	Do you mean the graphical abstract? We revised some words in the abstract and graphical abstract as suggested. However, the abstract is limited to 150 words so we tried as good and compact as possible to make the abstract readable and summarized the major findings.	An innovative, portable thermal composter was developed to accelerate the decomposition of food waste at household. The study aimed to evaluate the performance of the composter by assessing the quality of the compost produced. Food waste was chopped, mixed, stirred at 80 rpm, and heated to ~ 55 °C; thereafter, a bulking agent and stimulated microorganisms were added to the mixture. The composter mixing speed was assessed to calculate the feasible composting time. The results revealed that the active phase of composting process could be completed in a day, producing good quality compost. The pH, electric conductivity, and C/N ratio of the compost was 6.72, 1,148–1,179 µScm^{-1}, and 20.38, respectively. The lowest ammonia emissions (i.e., 7.2 g/Nm^{3}) were produced on the sixth day. The total cost required to process 1 kg of food waste in a day was only 2,097.76 Indonesian Rupiah (IDR), highlighting the feasibility of this technology.
3)	Highlights should consist of a short collection of bullet points that capture the novel results of your research as well as new methods that were used during the study. Kindly include some quantitative and	The highlights have been revised accordingly.	• An innovative portable food waste thermal composter was sucessfully developed • The active phase of composting was obtained on a day

No	Comments	Response	Modification
	quantitate finding of the research results. Please follow for more information at https://www.elsevier.com/authors/tools-and-resources/highlights.		• The composting process produce low ammonia emission (9.6 – 14.6 g/Nm^3) • The composter requires a small amount of energy, around 1.44 kWh/kg-waste • The produced compost can be a plant medium without passing the curing phase
4)	The author should enrich the MS with certain latest citations in particular area. For instance, food production for human consumption is lost or wasted, accounting for 1.3 billion tons of food per year data is seems old. Please update it from 2022. For instance, the author may follow https://www.sciencedirect.com/science/article/pii/S0960852422008410 article which describes the global release of waste food stream and their potential.	The sentences were updated as suggested. Some newly published references were added in the whole manuscripts.	Nearly a third of the worldwide food production for human consumption is lost or wasted, accounting for 1.3 billion tons of food per year. The high generation of food waste, representing a global economic loss, which is accounting around $400 billion per yar (Raj et al., 2022). The decrease in TN is caused by the evaporation of ammonia, and lower pH results in less organic matter mineralization (Wang et al., 2017). Food waste composting does not require labor, transport, sorting, or processing fees. Zhou et al. (2020) believe that the in-situ composting system differs from the centralized composting system. The total cost of the composter developed by Zhou et al. (2020) requires $0.033 (445.98 IDR) per kg for food waste, but the composting time is longer (four days). Even though the electricity cost is 2,097.76 IDR to process 1 kg of food waste in a day, food waste composting using a thermal composter still get profits from selling the compost product as a fertilizer for 5,000.00 IDR (Paduloh & Rosihan, 2021).
5)	Besides, the research gap, aim, and novelty statement	The novelty statement is added in the introduction as suggested	There are some techniques presented in previous literatures for reducing the processing time of household

No	Comments	Response	Modification
	should be given in details in the introduction.		composting. For instance, Kalamdhad et al. (2009) created a drum-shaped thermophilic composter consisting of chambers with varying temperatures at its chamber. The thermophilic conditions allow for microbial metabolism activation, accelerating the humification rate. The higher the temperature, the greater the microbiological activity will be (Ottani et al., 2022). Food waste composting with the addition of microorganisms and thermal elements (0-100 °C) reached the maximum temperature faster (3 days), and the maturation period decreased (4 weeks) (Charkhestani & Kebria, 2022). The composting time of 4 weeks is still contrary to the community's wishes, where they want the composting process to happen right after they throw the waste away in the composting machine. Awasthi et al. (2017) also found that adding multifunctional microorganisms produced better germination test results and a composting period of 20 days. A recent study reveals that adding biochar can increase the composting temperature and achieve an advanced thermophilic temperature in a short period of time. Thus, making the composting time lasted for only 20 days (Jain et al., 2018). Oktiawan et al. (2018) used a bulking agent at as much as 30% of the total waste to produce mature and stable compost. A processed food waste size of ± 2 mm is ideal for microbes to carry out the humification process and increase composting efficiency. Therefore, continuous aeration and rotation can also reduce the active phase of composting treatment from several weeks to only 4.5 days

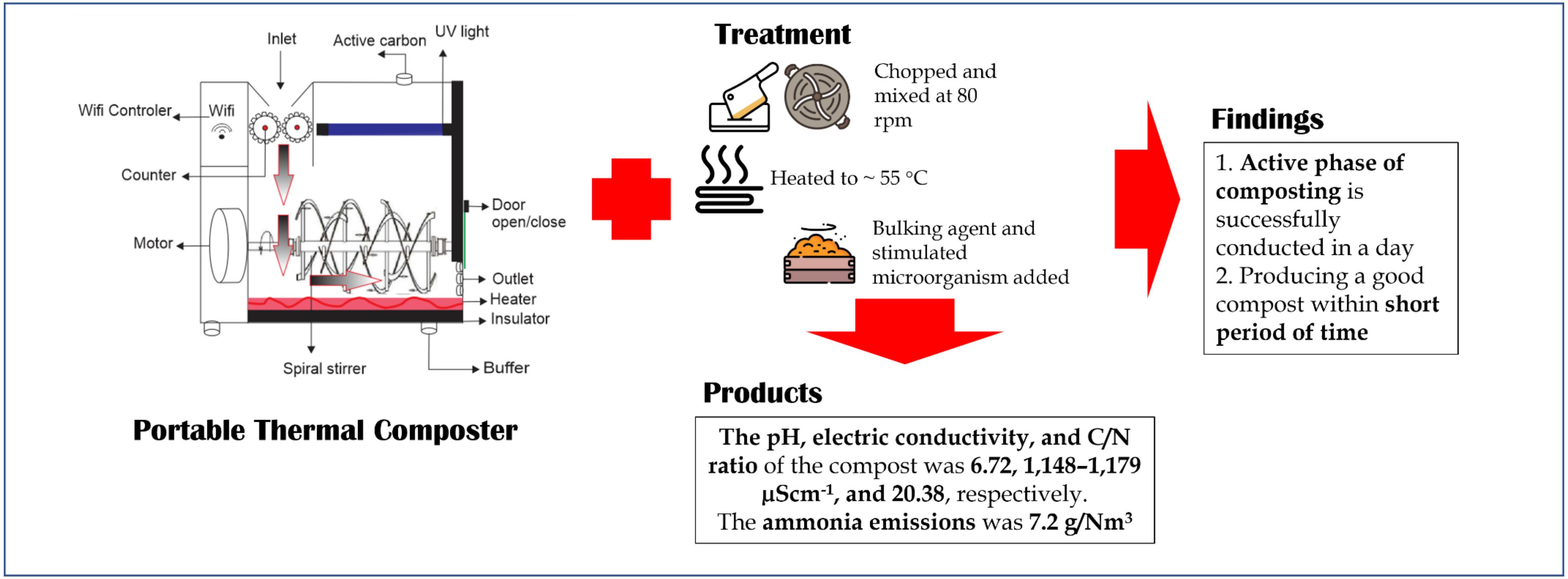
No	Comments	Response	Modification
			(Alkoaik, 2019). Since the processing time has become a limitation for applicability at the household level, some modifications are still required to increase its efficiency and ensure its feasibility as a household composter.
6)	Line no. 54 to 71 seems irrelevant. Please state the significance of this.	Thank you for your correction. We moved the sentences and rearranged the introduction section to make a better flow	Line 54 to 71 is moved
7)	Methods and material: The author should mention the exact temperature of through the MS. For instance, "the heater was set to ~ 80 °C. What is exact temperature for the reaction.	In the methods section, first paragraph, we added the information.	The heater was set to ~ 80 °C to accelerate the microbe metabolism and the humification rate
8)	SEM results are not satisfactory. Please state the significance of SEM analysis in particular study.	We added some explanations about the SEM results. The analysis is also added us suggested.	The same result was shown by Ajmal et al. (2021), where the food waste has tightened microscopic structure compared to the compost product. This result may be due to the microorganism activity, which reduces the particle size and increase the holes of the fermented food waste. Moreover, the surface roughness and irregular pore shapes shown in the compost product may indicate the possibility of microbial degradation during the composting process (Ma et al., 2022). **Fig. 5**. Surface morphology of (a) bulking agent, (b) food waste, and (c) compost produced from thermal composter at 10,000x magnification. The red arrows indicate the distribution of particle sizes and the circles indicate the pore diameters.
9)	What author means growth test. What are parameters	The growth test is to ensure that the compost produced from the active	"At 7 d, the plants were removed from the polybags, and several morphological parameters were

No	Comments	Response	Modification
	selected to measure the growth terms and what aspect.	phase of composting can be used as plant growth medium or not. The concept of the test is nearly the same with the germination test. However, we followed the methods by Nguyen et al., (2020) where in their research, they mentioned about "vegetable-growth experiments"	measured, including height, weight, root length, and the number of leaves. The plant heights were measured using a ruler, plant weights were measured using an analytical balance (Mettler Toledo, Switzerland), and the germination rates were observed daily."
10)	Section 3.2, the effect of pH and temperature needs to be clarified. The results are properly discussed in every aspect. Please revise this section.	Thank you for your comments. We added some discussion related to this matter in this section as suggested.	The daily addition of food waste did not significantly alter the mixture's pH, with the mixture at 1 and 7 d having pHs of 6.72 and 7.01, respectively. This pH range is ideal for developing bacteria and fungi, thus, contributing to the composting process in producing high-quality and mature compost. The thermophilic temperature positively impacts the decomposition rate of food waste so that the composting process can be completed in a day. In addition, this thermophilic temperature decreases food waste's water content, where the initial 86.64% food wastewater content decreases to 32.58% (day 1) and 23.89% (day 7).
11)	Section 3.11, what parameters the author have selected for economic evaluations. Please include the system boundaries and variable. For instance, water ratio, energy input, feed stock costing, mechanical processing cost etc. Please elaborate in details as the discussion provided seems not sufficient to describe novelty.	We made a modification on the title: 3.11. Practical Evaluation and Future Research Direction The system boundaries are mentioned and discussed briefly. Therefore, the water ratio and other parameter is descriptively explained. We hoped that the	Household food waste composting does not require labor, transport, sorting, or processing fees. Zhou et al. (2020) believe that the in-situ composting system differs from the centralized composting system. The thermal composter used in this study processed 1 kg of food waste per day, using a total electrical power of 1.452 kWh. This total power consists of the shredding unit (i.e., 0.00375 kWh), the spiral stirring unit (i.e., 0.00828 kWh), and the heating unit (i.e., 1.440

No	Comments	Response	Modification
		additional information can enhance the readability and is sufficient to explain the novelty.	kWh). To process 1 kg of food waste in a day, the heating unit required the most power as it operated for 24 h, while the shredding and stirring units operated for only 30 and 80 s, respectively. The total cost for operating the thermal composter amounted to 2,097.76 IDR to process 1 kg of food waste in a single day. The total cost of the composter developed by Zhou et al. (2020) requires $0.033 (445.98 IDR) per kg for food waste, but the composting time is longer (four days). Even though the electricity cost is 2,097.76 IDR to process 1 kg of food waste in a day, food waste composting using a thermal composter still get profits from selling the compost product as a fertilizer for 5,000.00 IDR (Paduloh & Rosihan, 2021). Moreover, the compost improves soil quality, assists the remediation of contaminated soil and reduces the need for chemical fertilizers. Solar cells can be an alternative AC power source for thermal composter operations. In addition, it is necessary to increase public acceptance of the thermal composter so that they can use it to treat food waste.
12)	Conclusion needs to be revise with clear emphasis on the future application of the current results	Because the limitation of the number of words in the conclusion section (only 100 words), we changed the “economic evaluation” section into “practical evaluation and future research direction” which emphasize the future application of the current results.	Moreover, the compost improves soil quality, assists the remediation of contaminated soil and reduces the need for chemical fertilizers. Solar cells can be an alternative AC power source for thermal composter operations. In addition, it is necessary to increase public acceptance of the thermal composter so that they can use it to treat food waste.
Editor Comments			

No	Comments	Response	Modification
1)	Each highlight must not exceed 85 characters including space.	We confirm that the highlights are not exceeding 85 characters. We revised the highlights as reviewer 2 suggested	• An innovative portable food waste thermal composter was sucessfully developed • The active phase of composting was obtained on a day • The composting process produce low ammonia emission (9.6 – 14.6 g/Nm^3) • The composter requires a small amount of energy, around 1.44 kWh/kg-waste • The produced compost can be a plant medium without passing the curing phase
2)	Conclusions must not exceed 100 words.	We confirm that the conclusion is consisted of 98 words.	-
3)	Reference format must be correct.	As it is mentioned by first reviewer, we changed the references format as per journal guideline.	Included in the manuscript
4)	Maximum number of figures and tables allowed is six.	We confirm that the number of figures and tables in the manuscript is 6.	-
5)	Supplementary materials must not be quoted in main manuscript as Table S1 or Figure S1 (must be, 'as given in supplementary material') - No abbreviations in title, - No single column tables (such as characterisation of biomass), - No single parameter figure, - No routine spectra, etc such as SEM, X-ray, FTIR, etc, - No photos of simple equipment or lab set-up, - NO TABLE REPORTING OTHERS RESULTS AND OWN RESULTS (such tables are only in reviews)	As it is mentioned that SEM cannot be placed in supplementary materials so we replaced the SEM is moved to the manuscript	SEM result is moved from the supplementary files to the manuscript.

Graphical Abstract (for New review)



HIGHLIGHTS

- An innovative portable food waste thermal composter was sucessfully developed
- The ~~Mature~~ active phase of ~~and stable~~ composting was obtained on a ~~single~~ day
- The composting process produce low ammonia emission (9.6 – 14.6 g/Nm^3)~~concentration~~
- The ~~thermal~~ composter requires a small amount of energy ~~to produce high quality compos~~, ~~t~~around 1.44 kWh/kg-waste
- The produced compost can be a plant medium without passing the curing phase
-

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

LAMPIRAN 3

An Innovative Thermal Composter to Accelerate Food Waste Decomposition at the Household Level

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ABSTRACT

An innovative, portable thermal composter was developed to accelerate the decomposition of food waste at household. The study aimed to evaluate the performance of the composter by assessing the quality of the compost produced. Food waste was chopped, mixed, stirred at 80 rpm, and heated to ~ 55 °C; thereafter, a bulking agent and stimulated microorganisms were added to the mixture. The composter mixing speed was assessed to calculate the feasible composting time. The results revealed that the active phase of composting process could be completed in a day, producing good quality compost. The pH, electric conductivity, and C/N ratio of the compost was 6.72, 1,148–1,179 µScm^{-1}, and 20.38, respectively. The lowest ammonia emissions (i.e., 7.2 g/Nm^{3}) were produced on the sixth day. The total cost required to process 1 kg of food waste in a day was only 2,097.76 Indonesian Rupiah (IDR), highlighting the feasibility of this technology.

Keywords: food waste; active phase; rapid composter; thermal composter

1. INTRODUCTION

Nearly a third of the worldwide food production for human consumption is lost or wasted, accounting for 1.3 billion tons of food per year. The high generation of food waste, representing a global economic loss, which is accounting around $400 billion per yar (Raj et al., 2022). Among various other types of waste, food waste may generate the highest greenhouse gas (GHG) emissions, as it produces an enormous number of contaminants through natural microbial degradation and other indirect processes, including transportation and the use of food processing machinery (Shen et al., 2020). Therefore, preventing food waste at the household level, downstream of the food supply chain, is critical in limiting climate change (Parfitt et al., 2010).

There are several food waste management strategies, including composting (Cesaro et al., 2019), animal feed (Mo et al., 2018), anaerobic/aerobic digestion (Wainaina et al., 2020), gasification, incineration (You et al., 2016), pyrolysis (Kim et al., 2020), and direct landfill disposal (Goodman-Smith et al., 2020). Composting remains the most widespread solution in developing countries, where it treats ~ 90–96% of food waste (Thi et al., 2015). Effective food waste management has been proven to reduce pollutants, odors, and GHG emissions (Wei et al., 2017; Zaman et al., 2021). In addition, composting is a common practice that can be easily implemented in residential households.

Composting systems at the household and community level have been discussed by Lu and Sidortsov (2019). Household-level composting equipment allows residents to compost their food waste, ultimately reducing the volume of domestic waste transported to communal waste processing facilities. There are, however, some challenges facing composting systems at the household level. For example, there is the likelihood of odor emissions during the biodegradation process (Zhou et al., 2020). Moreover, the long processing times involved with composting may lead to residents being unwilling to compost in their homes. The success of household-level composting also depends on the knowledge, capacity, and self-awareness of the residents who manage the household's waste (Fadhullah et al., 2022).

There are some techniques presented in previous literatures for reducing the processing time of household composting. For instance, Kalamdhad et al. (2009) created a drum-shaped thermophilic composter consisting of chambers with varying temperatures at its chamber. The thermophilic conditions allow for microbial metabolism activation, accelerating the humification rate. The higher the temperature, the greater the microbiological activity will be (Ottani et al., 2022). Food waste composting with the addition of microorganisms and thermal elements (0-100 °C) reached the maximum temperature faster (3 days), and the maturation period decreased (4 weeks) (Charkhestani & Kebria, 2022). The composting time of 4 weeks is still contrary to the community's wishes, where they want the composting process to happen right after they throw the waste away in the composting machine. Awasthi et al. (2017) also found that adding multifunctional microorganisms produced better germination test results and a composting period of 20 days. A recent study reveals that adding biochar can increase the composting temperature and achieve an advanced thermophilic temperature in a short period of time. Thus, making the composting time lasted for only 20 days (Jain et al., 2018). Oktiawan et al. (2018) used a bulking agent at as much as 30% of the total waste to produce mature and stable compost. A processed food waste size of ± 2 mm is ideal for microbes to carry out the humification process and increase composting efficiency. Therefore, continuous aeration and rotation can also reduce the active phase of composting treatment from several weeks to only 4.5 days (Alkoaik, 2019). Since the processing time has become a limitation for applicability at the household level, some modifications are still required to increase its efficiency and ensure its feasibility as a household composter.

This study developed an innovative household composter with several modifications which fill research gaps and addresses issues presented in previous studies. Furthermore, the composter designed here is simple to use, portable, and operated automatically. Essentially, food waste was stirred, heated, mixed, and decomposed in the composter, allowing active phase of composting to be obtained within a short period. The aim of the study was to demonstrate the utility of a thermal composter prototype in different operational environments. Furthermore, due to the limited research and the importance for further developing food waste management strategies at the household level, the goal of this study was to demonstrate a thermal composter that may accelerate the food waste composting process. The focus here was on compost quality and morphology, ammonia (NH_3) gas emissions, and the total operating cost.

2. METHODS

This research was conducted in the greenhouse of the Environmental Engineering Department, Faculty of Engineering, Diponegoro University. The thermal composter (see Fig. 1) was made of stainless steel (Type 316 austenitic, Indonesia) with dimensions of 60 cm × 30 cm × 55 cm (length × width × height). The composter frame was made of corrosion-resistant galvalume, and its outer layer was made of white and green acrylic. The thermal composter consisted of an inlet chamber, a food waste chopper, a spiral stirrer driven by a motor (0.5 hp, 3-phase, 1370 rpm, China), and a heater (12 V). The heater was set to ~ 80 °C to accelerate the microbe metabolism and the humification rate. The bottom and sides of the composter were equipped with insulators to reduce heat loss. Finally, activated carbon and a UV lamp were attached to the top of the composter to remove odors and microorganisms resulting from the food waste decomposition (Zhou et al., 2020)

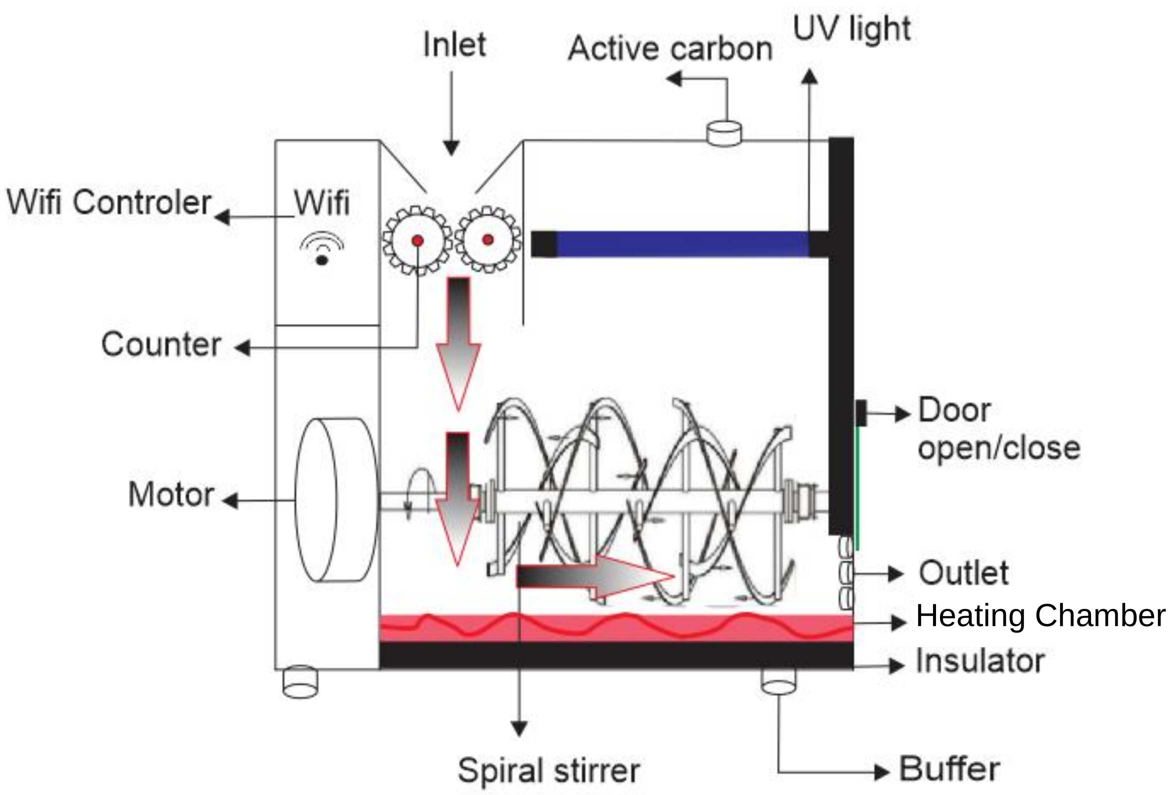


Fig. 1. Schematic diagram illustrating the design of the thermal composter developed in this study.

Food waste was collected from a restaurant in Semarang City using trash bags and transported to the Environmental Laboratory, Faculty of Engineering, Diponegoro University for analysis. Prior to starting the experiment, the composition and physical properties of the food waste were determined; thereafter, the food waste was mixed. The bulking agent used here came from mature and stable compost with a size of 100 mesh. The food waste consisted of various and mixed ingredients such as leftover rice, spinach, chayote, banana peels, vegetable gravy, and many more. First, food waste (500 g per day) was added to the composter inlet and chopped until the food waste particle size was homogenized to ~ 2 cm. Thereafter, the bulking agent was added, accounting for as much as 30% (v/v) of the total food waste. The mixture was then periodically stirred by the spiral stirrer and slowly pushed into the heating chamber, where it was rotated for 1 min every 6 h. Despite the heater being set to 80 °C, the mixture's temperature gradually decreased to 28–30 °C while in the cooling compartment or outlet chamber. The composting cycle was carried out for 7 d by adjusting the rotational speed of the spiral stirrer to 80 rpm. Compost was removed via the outlet chamber, with samples collected daily and stored at 4 °C until further analysis.

Laboratory tests were conducted to ensure that the compost was actively produced. Compost quality was assessed using the following parameters: (a) moisture content (MC), (b) electric conductivity (EC), (c) pH, (d) temperature, (e) total nitrogen (TN), and (f) total organic carbon (TOC). The gravimetric method was used to determine the MC, with the sample being heated to 105 °C using an oven (Memmert UN 50, Germany). The Kjeldahl method was used to determine TN, while TOC was assessed using the Walkley-Black method (UV-Vis 150 Spectrophotometer, Thermo Fisher Scientific, USA). The NH_3 emissions were assessed using the indophenol method and a spectrophotometer (Indonesia National Standard – SNI 19-7119.1-2005). The compost surface morphology was assessed using scanning electron microscopy (SEM) (Phenom ProX Desktop Scanning Electron Microscope, Thermo Fisher Scientific, USA) at a magnification of 100,000x. To do so, 2 g samples of three compost components (i.e., the bulking agent, food waste, and final compost) were collected and oven-dried at 110 °C for 48 h (Memmert, Germany). The sample was ground, sieved through 200 mesh and fixed on a stub (circular metallic plate holder). Thereafter, the sample was sputter coated with gold (Sputter Coater, Quorum Q300T D Plus, UK), ensuring visibility of the morphology.

Plant growth tests were conducted to assess the quality of the compost as a plant growth medium. This was done following the procedure described in Nguyen et al. (2020). Mung bean (*Vigna radiata*) plants sourced from a farm shop (Semarang, Indonesia) were planted in nine polybags of 5 cm × 15 cm (width × height) containing compost samples. All plants were treated equally and received the same daily watering. At 7 d, the plants were removed from the polybags, and several morphological parameters were measured, including height, weight, root length, and the number of leaves. The plant heights were measured using a ruler, plant weights were measured using an analytical balance (Mettler Toledo, Switzerland), and the germination rates were observed daily. The presence of flies and odors was recorded following the methodology described in Lleó et al. (2013). Finally, an economic evaluation was undertaken, aiming to assess the total costs incurred while operating the thermal composter. The total electrical power required for each component of the composter was converted into Indonesian Rupiah (IDR). Components that required electric power were the chopper, heater, spiral stirrer, and UV lamp. Replacement costs of the activated carbon and bulking agent were also calculated in detail. No labor or transportation costs were incurred.

3. RESULTS AND DISCUSSION

3.1. Moisture Content (MC)

The food waste contained an MC of 86.64% (Table 1); this was much higher than the recommended MC (i.e., 40–60%) for favorable microbial growth (Guidoni et al., 2018). However, food waste can produce a significant amount of gas and favors anaerobic processes, which in turn can produce foul odors and contribute to the emission of GHGs (Onwosi et al., 2017). The bulking agent contained an MC of 43.16% (Table 1). Despite this, during the composting process, the MC of the food waste and bulking agent mixture decreased drastically to 32.58% after 24 h (Table 1); this was due to the chopping, heating, and stirring that took place in the thermal composter. Water in the food waste evaporated during the heating and thermophilic composting process; this resulted in the MC decreasing to 19.76% at 4 d, while at 5 and 7 d, MCs increased to 23.55% and 23.89%, respectively (Table 1).

The microbes almost became inactive after the MC dropped below 20%; at this stage, the compost products could have been bagged (Zhou et al., 2020). The bulking agent, owing to its compression resistance, helped maintain the porosity and structure of the mixture during composting. Indeed, no leachate was observed, indicating that the addition of the bulking agent influenced the total amount of leachate formed during composting (Guidoni et al., 2018). Finally, the stirring frequency helped maintain the porosity of the mixture and added oxygen to the system.

Table 1. Compost quality parameters and growth test results.

Parameter	**Units**	**FW**	**BA**	**C-1**	**C-2**	**C-3**	**C-4**	**C-5**	**C-6**	**C-7**
MC	%	86.64	43.16	32.58	25.00	25.50	19.76	23.55	24.07	23.89
pH	-	6.63	6.70	6.72	6.32	6.49	6.53	6.72	6.27	7.01
EC	μScm^{-1}	1,591	3,270	891	1,148	1,124	1,435	960	1,170	1,179
Growth test										
Height	cm	0	7.8	25.3	24.8	20.8	21.7	0	18.5	12.4
Weight	g	0	0.2403	0.4512	0.5116	0.4413	0.5308	0	0.5061	0.4843
Root length	cm	0	1.5	5.2	4.5	4.4	4.2	0	2.3	1
Leaf	single leaves	0	2	2	2	2	2	0	2	2

FW, food waste; BA, bulking agent; C-1–C-7, daily composting results (i.e., 7 d).

3.2. pH and Temperature

The food waste had an original pH of 6.63, while the bulking agent had a pH of 6.70 (Table 1). The daily addition of food waste did not significantly alter the mixture's pH, with the mixture at 1 and 7 d having pHs of 6.72 and 7.01, respectively. This pH range is ideal for developing bacteria and fungi, thus, contributing to the composting process in producing high-quality and mature compost. Yuan & Zhu (2016) stated that the addition of a bulking agent accelerates the increase in pH. Typically, food waste that undergoes natural decomposition produces an acidic pH due to the formation of organic acid (Guidoni et al., 2018). The pH then begins to increase due to the ammonification of organic matter, where organic nitrogen is transformed into amide and ammoniacal nitrogen. The formation of NH_3, an alkaline reaction, also increases the pH. Zhou et al. (2020) found that processing food waste using a composter produced weakly acidic pHs during the initial and cooling stages, while an increase in pH was observed during the heating and thermophilic stages. Ultimately, the changes in pH may be attributable to pH imbalances caused by the microbial metabolic activity. Based on the pH value results, compost produced by the thermal composter could be taken during any of the seven composting process days and be used for agricultural purposes.

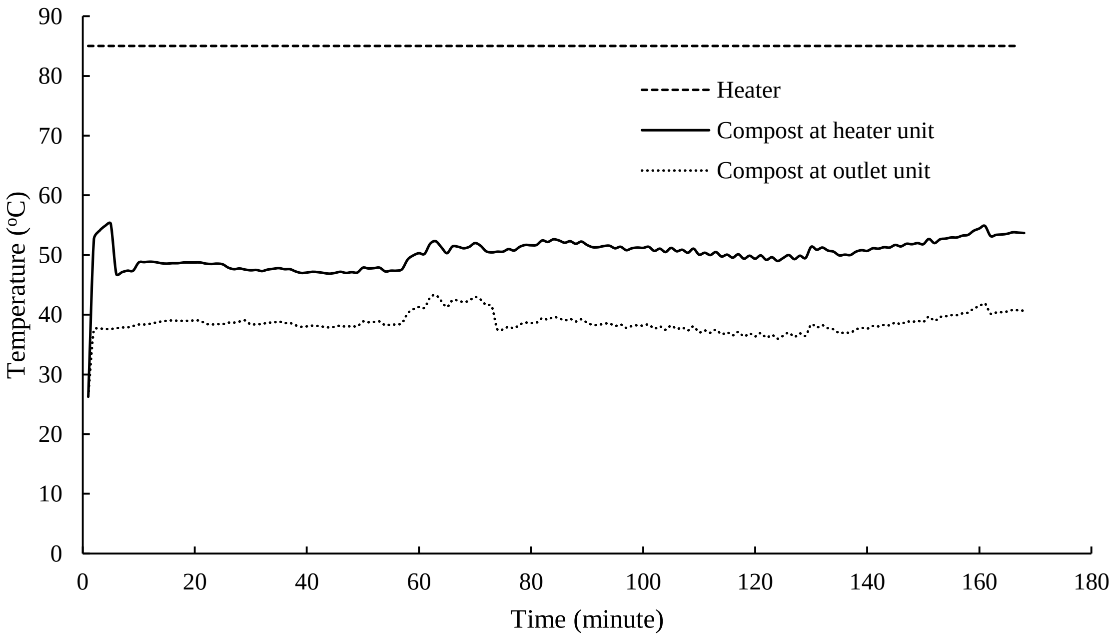


Fig. 2. Graph illustrating the temperature of the thermal composter heater (dashed line), as well as the compost temperature in the heating (solid line) and outlet chambers (dotted line).

The heater of the thermal composter was set to 80 °C, ensuring consistent thermophilic conditions in the heating chamber (Fig. 2). The composting temperature in the heating chamber rose rapidly from 26.3 °C to 52.63 °C within the first 20 min (Fig. 2). Within the same period, however, the composting temperature in the outlet chamber only rose from 26.3 °C to 37.44 °C (Fig. 2). A temperature of 52.63 °C in the heating chamber was beneficial for thermophilic microbial metabolism. At 7 d, the compost temperatures in the heating and outlet chambers were 53.69 °C and 40.69 °C, respectively (Fig. 2), indicating rapid food waste composting in the thermal composter. The thermophilic temperature positively impacts the decomposition rate of food waste so that the composting process can be completed in a day. In addition, this thermophilic temperature decreases food waste's water content, where the initial 86.64% food wastewater content decreases to 32.58% (day 1) and 23.89% (day 7).

3.3. Electric Conductivity (EC)

The original food waste and bulking agent EC values were 1,591 μScm^{-1} and 3,270 μScm^{-1}, respectively. The mixture had an EC value of 0.891 μScm^{-1} after being processed for 1 d in the thermal composter. The observed EC value decrease was due to the chopping, heating, and thermophilic decomposition that occurred in the thermal composter. However, the overall EC value during the composting process did not alter significantly and had a range of 1,148–1,179 μScm^{-1}. EC values reflect the salinity of the composting matrix (Onwosi et al., 2017). Furthermore, compost is safe for planting when it displays an EC value < 4,000 μScm^{-}

[1]. In this study, EC values were consistently < 2,000 μScm^{-1} during the composting process, and thus, had no impact on biological activity (Mujtaba et al., 2021).

3.4. Flies and Odor

Flies typically land on food waste soon after its disposal. However, in this study, no flies were observed for 7 d, implying that the food waste and the products of its decomposition did not attract flies. Stirring of the mixture every 6 h did not affect the number of flies. A previous study found that the capacity of the composter was sufficient to stabilize the organic waste (Blazy et al., 2014). Guidoni et al. (2018) found that flies disappeared after the eleventh day of composting three treatments which varied in their ratio of rice husk to raw fruit and vegetables (i.e., 70:30, 50:50, 30:70; v:v). No strong odor was detected during this study. The bulking agent addition allowed the diffusion of gases and it maintained an aerobic composting process. In addition, bulking agents enhanced the inter-particle voids in the composite pile, thereby increasing the air permeability and regulating the humidity of the compost substrate (Yang et al., 2019).

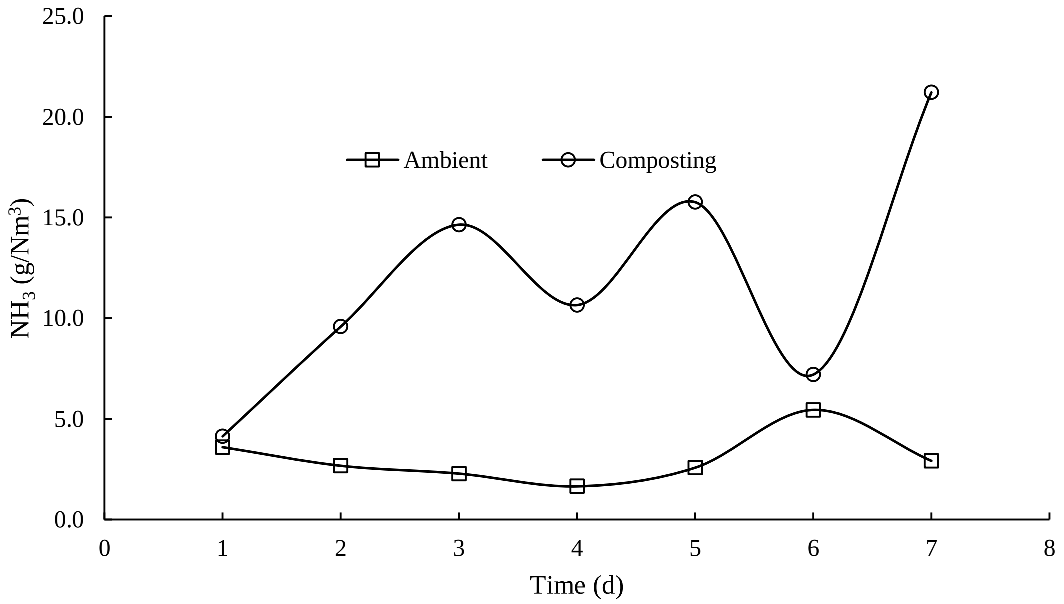


Fig. 3. Graph illustrating ammonia (NH_3) concentrations in ambient air (squares) and NH_3 emissions during seven days of composting using a thermal composter (circles).

3.5. NH_3 Emissions

Emission of NH_3 varies according to the substrate composition, particle sizes, moisture, oxygen distribution, initial temperature gradients, and the overall process conditions (Onwosi et al., 2017). The first day of the composting process produced an NH_3 emission of 4.1 g/Nm^3, with an increase to 9.6 g/Nm^3 occurring at 2 d (Fig. 3). This increase was likely due to the addition of food waste; moreover, the increasing trend continued until 7 d, which saw an NH_3 emission of 21.2 g/Nm^3 (Fig. 3). The NH_3 concentrations in ambient air ranged from 1.6–5.4 g/Nm^3, with the lowest concentration (i.e., 1.6 g/Nm^3) occurring at 4 d and the highest concentration (i.e., 5.4 g/Nm^3) at 6 d (Fig. 3). Overall, the NH_3 concentrations in ambient air did not change significantly ($p > 0.05$).

3.6. Total Organic Carbon (TOC)

Higher levels of TOC degradation indicate more stable compost (Sharma et al., 2017). After 1 d in the thermal composter, the TOC of the compost mixture decreased drastically by 75.94%. The TOC for the remaining days ranged from 77.42–79.94%, lower than the initial TOC level (See Fig. 4). The decrease observed here supports Lalremruati & Devi (2021), who stated that the decomposition of vegetable waste is straightforward, owing to it mostly containing cellulose. Liu et al. (2018) reported a decrease in vegetable waste TOC ranging from 11.4–32.1%, when using sawdust, cow dung, and inoculum for 40 d. Notably, the TOC decrease observed in this study remained stable (i.e., 77.42–79.94%) throughout the 7-d period, despite the addition of 500 g of food waste per day (Fig. 4). Indeed, these results indicate that the thermal composter is effective in accelerating the degradation of TOC, owing to the integration of the mixing system, heating parameters, and bulking agent.

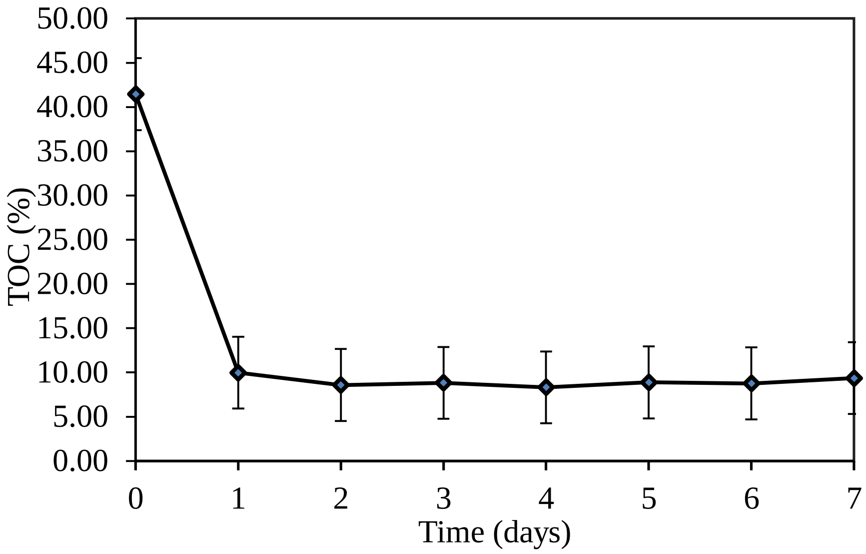


Fig. 4. Graph illustrating the level of total organic carbon (TOC) in food waste during seven days of composting using a thermal composter.

3.7. Total Nitrogen (TN)

The initial TN value decreased significantly at 2 and 3 d of the composting process. The decrease in TN is caused by the evaporation of ammonia, and lower pH results in less organic matter mineralization (Wang et al., 2017). As it may see in Fig. 3, the ammonia emission increased from 9.6 to 14.6 g/Nm^3. Therefore, the pH values for 2 and 3 d remain at 6.32 and 6.49, respectively, which are lesser than the pH at 1, 4, 5, and 7 d. Indeed, several studies have attributed the decrease in TN to the volatilization of NH_3, when temperature and pH were more than 45 °C (Cáceres et al., 2018; Zhou et al., 2018). Nguyen et al. (2020) found that TN was influenced by temperature; in addition, the optimal TN was found in experiments that were rotated once per day and exhibited a C/N ratio of 20. Regarding the production of compost from domestic organic waste (Indonesia National Standard – SNI 19-7030-2004), the optimal TN for compost is a minimum of 0.40%. Indeed, the results obtained here confirm that the TN content in the compost collected at 1, 4, 6, and 7 d meet this quality standard. The highest TN content (i.e., 0.49%) was found on the first day, while the lowest TN content (i.e., 0.28%), which does not meet the quality standard, was found at 3 d. Ultimately, temperature and the composition of the compost raw material can affect the TN in the compost.

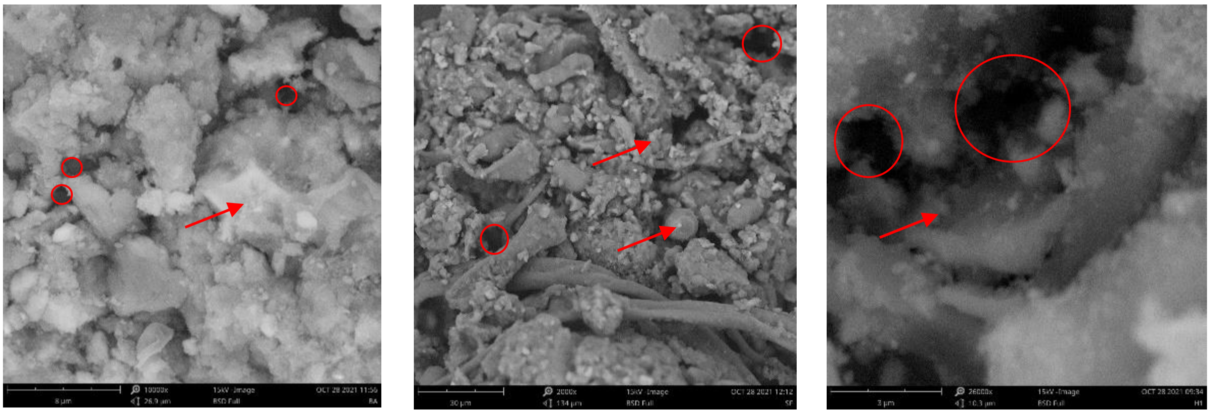
3.8. C/N Ratio

The C/N ratio is a conventional parameter used to assess the composting process (Zhou et al., 2018). The reduction of the C/N ratio due to the simultaneous consumption of carbon and nitrogen organic substrates indicates an effective composting process (Wang et al., 2016), with composts that display a C/N ratio < 20 being considered mature. According to the Ministry of Agriculture of Indonesia Number: 28/Permentan/SR.30/5/2009, organic and biological fertilizers, as well as soil enhancers, typically exhibit C/N ratios within the range of 15–25. The composting process in this study was 500 g of food waste being used as the initial compost raw material; on each of the ensuing days, an additional 500 g of food waste with a typical composition was added. The results reveal that the food waste at 2, 3, and 5 d had C/N ratios > 25, ultimately displaying poor composting conditions; whereas at 1, 4, 6, and 7 d, the C/N ratios ranged from 20–25, indicating good compositions. The C/N ratio variation found in this study was ultimately driven by differences in the daily food waste composition and quantity.

3.9. SEM Images

SEM was used as an additional technique to assess micro-changes in the surface morphology of different compost components (See Fig. 5). In SEM, a focused high-energy electron beam is used to scan the surface of a specimen (Oñiguez et al., 2011). The resulting high-quality images provide information about the sample's external morphology (texture) and crystalline structure. Micrographs of food waste samples, compost, and the bulking agent (as

provided in supplementary materials) reveal different particle sizes and distributions per unit area, as well as heterogeneity in particle compaction. Moreover, micrographs showed that the compost sample exhibited larger pore diameters and had no particle compaction. However, while the initial food waste displayed small pore diameters, particle compaction was present. Biodegradation has been shown to lead to improved texture and particle compaction (Arora & Kaur, 2019). The same result was shown by Ajmal et al. (2021), where the food waste has tightened microscopic structure compared to the compost product. This result may be due to the microorganism activity, which reduces the particle size and increase the holes of the fermented food waste. Moreover, the surface roughness and irregular pore shapes shown in the compost product may indicate the possibility of microbial degradation during the composting process (Ma et al., 2022).



(a) (b) (c)

Fig. 5. Surface morphology of (a) bulking agent, (b) food waste, and (c) compost produced from thermal composter at 10,000x magnification. The red arrows indicate the distribution of particle sizes and the circles indicate the pore diameters.

3.10. Growth test

Compost products derived from food waste generally provide improved plant growth conditions. The plant growth tests revealed rapid and consistent daily mung bean growth.

Growth tests using compost taken from six of the seven composting days (i.e., 1–4, 6, and 7 d) as well as the bulking agent alone, resulted in increased plant height and weight (Table 1). Growth tests using the fresh food waste alone, however, did not facilitate any plant growth (Table 1), with the waste beginning to rot at 1 d. Moreover, no plant growth was observed t 5 d (Table 1); this was due to the accumulation of acidic decomposition products. Ultimately, the results presented here agree with the literature that compost from food waste can be used as a plant growth medium (Nguyen et al., 2020).

3.11. Practical Evaluation and Future Research Direction

Household food waste composting does not require labor, transport, sorting, or processing fees. Zhou et al. (2020) believe that the in-situ composting system differs from the centralized composting system. The thermal composter used in this study processed 1 kg of food waste per day, using a total electrical power of 1.452 kWh. This total power consists of the shredding unit (i.e., 0.00375 kWh), the spiral stirring unit (i.e., 0.00828 kWh), and the heating unit (i.e., 1.440 kWh). To process 1 kg of food waste in a day, the heating unit required the most power as it operated for 24 h, while the shredding and stirring units operated for only 30 and 80 s, respectively. The total cost for operating the thermal composter amounted to 2,097.76 IDR to process 1 kg of food waste in a single day. The total cost of the composter developed by Zhou et al. (2020) requires $0.033 (445.98 IDR) per kg for food waste, but the composting time is longer (four days). Even though the electricity cost is 2,097.76 IDR to process 1 kg of food waste in a day, food waste composting using a thermal composter still get profits from selling the compost product as a fertilizer for 5,000.00 IDR (Paduloh & Rosihan, 2021). Moreover, the compost improves soil quality, assists the remediation of contaminated soil and reduces the need for chemical fertilizers. Solar cells can be an alternative AC power source for thermal composter operations. In addition, it is necessary to increase public acceptance of the thermal composter so that they can use it to treat food waste.

4. CONCLUSION

Thermal composting is considered a straightforward and effective strategy to manage household food waste. In this study, an innovative household thermal composter was developed and its feasibility assessed. Active phase of composting was finished after a single day of treatment, with MC, pH, temperature, EC, TOC, TN, C/N ratios, and SEM images meeting the criteria required for high quality compost. Regardless, the compost obtained after a single day was used successfully as a plant growth medium, confirming the compost's low toxicity level. Furthermore, the composter was shown to require a small amount of daily electricity to process food waste.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest exists.

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An Innovative Thermal Composter to Accelerate Food Waste Decomposition at the Household Level

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ABSTRACT

An innovative, portable thermal composter was developed to accelerate the decomposition of food waste at household. The study ~~also~~ aimed to evaluate the performance of the composter by assessing the quality of the compost produced. Food waste was chopped, mixed, stirred at 80 rpm, and heated to ~ 55 °C; thereafter, a bulking agent and stimulated microorganisms were added to the mixture. The composter mixing speed was assessed to calculate the feasible composting time. The results revealed that the active phase of composting process could be completed in a ~~single~~ day, producing ~~high quality, mature~~ good quality compost. The pH, electric conductivity, and C/N ratio of the compost was 6.72, 1,148–1,179 μScm^{-1}, and 20.38, respectively. The lowest ammonia emissions (i.e., 7.2 g/Nm^3) were produced on the sixth day. The total cost required to process 1 kg of food waste in a day was only 2,097.76 Indonesian Rupiah (IDR), highlighting the feasibility of this technology.

Keywords: food waste; ~~mature~~ active phase~~compost~~; rapid composter; thermal composter

1. INTRODUCTION

Nearly a third of the worldwide food production for human consumption is lost or wasted, accounting for 1.3 billion tons of food per year. The high generation of food waste, representing a global economic loss, which is accounting around $400 billion per yar ~~-~~(Raj et al., 2022~~Schanes et al., 2018~~). Among various other types of waste, food waste may generate the highest greenhouse gas (GHG) emissions, as it produces an enormous number of contaminants through natural microbial degradation and other indirect processes, including transportation and the use of food processing machinery (Shen et al., 2020). Therefore, preventing food waste at the household level, downstream of the food supply chain, is critical in limiting climate change (Parfitt et al., 2010).

There are several food waste management strategies, including composting (Cesaro et al., 2019), animal feed (Mo et al., 2018), anaerobic/aerobic digestion (Wainaina et al., 2020), gasification, incineration (You et al., 2016), pyrolysis (Kim et al., 2020), and direct landfill disposal (Goodman-Smith et al., 2020). Composting remains the most widespread solution in developing countries, where it treats ~ 90–96% of food waste (Thi et al., 2015). Effective food waste management has been proven to reduce pollutants, odors, and GHG emissions (Wei et al., 2017; Zaman et al., 2021). ~~Awasthi et al. (2017) also found that adding multifunctional microorganisms produced better germination test results and a composting period of 20 d. Nevertheless,~~ In addition, composting is a common practice that can be easily implemented in residential households.

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Composting systems at the household and community level have been discussed by Lu and Sidortsov (2019). Household-level composting equipment allows residents to compost their food waste, ultimately reducing the volume of domestic waste transported to communal waste processing facilities. There are, however, some challenges facing composting systems at the household level. For example, there is the likelihood of odor emissions during the biodegradation process (Zhou et al., 2020). Moreover, the long processing times involved with composting may lead to residents being unwilling to compost in their homes. The success of household-level composting also depends on the knowledge, capacity, and self-awareness of the residents who manage the household's waste (Fadhullah et al., 2022).

~~Several studies have discussed how to accelerate the composting process, as well as reduce the odors and GHGs emitted during the process. For instance, Kalamdhad et al. (2009) created a drum-shaped thermophilic composter consisting of chambers with varying temperatures, namely the inlet (60–70 °C), processing (50–60 °C), and outlet chamber (30–38 °C). The thermophilic conditions allow for microbial metabolism activation, accelerating the humification rate. Composters are also able to exhibit an aeration process which reduces the~~

~~odors and GHGs emitted by the anaerobic decomposition (Zaman et al., 2021). Margaritis et al. (2018) found that compost physical properties increased as a result of an increase in the porosity of different bulking agents, which in turn allowed for better aeration. Oktiawan et al. (2018) used a bulking agent at as much as 30% of the total waste to produce mature and stable compost. A processed food waste size of ± 2 mm is ideal for microbes to carry out the humification process and increase composting efficiency. Awasthi et al. (2017) also found that adding multifunctional microorganisms produced better germination test results and a composting period of 20 d. Nevertheless, Blazy et al. (2014) suggests that olfactory measurements should be correlated with gaseous emissions to allow for a more accurate evaluation of odor emissions during food waste composting. Thermal composters are known for having a faster composting process; however, some modifications are required to increase its efficiency and ensure its feasibility as a household composter.~~There are some techniques presented in previous literatures for reducing the processing time of household composting. For instance, Kalamdhad et al. (2009) created a drum-shaped thermophilic composter consisting of chambers with varying temperatures at its chamber~~, namely the inlet (60–70 °C), processing (50–60 °C), and outlet chamber (30–38 °C)~~. The thermophilic conditions allow for microbial metabolism activation, accelerating the humification rate. The higher the temperature, the greater the microbiological activity will be (Ottani et al., 2022). Food waste composting with the addition of microorganisms and thermal elements (0-100 °C) reached the maximum temperature faster (3 days), and the maturation period decreased (4 weeks) (Charkhestani & Kebria, 2022). The composting time of 4 weeks is still contrary to the community's wishes, where they want the composting process to happen right after they throw the waste away in the composting machine. Awasthi et al. (2017) also found that adding multifunctional microorganisms produced better germination test results and a composting period of 20 days. A recent study reveals that adding biochar can increase the composting temperature and achieve an advanced thermophilic temperature in a short period of time. Thus, making the composting time lasted for only 20 days (Jain et al., 2018). Oktiawan et al. (2018) used a bulking agent at as much as 30% of the total waste to produce mature and stable compost. A processed food waste size of ± 2 mm is ideal for microbes to carry out the humification process and increase composting efficiency. Therefore, continuous aeration and rotation can also reduce the active phase of composting treatment from several weeks to only 4.5 days (Alkoaik, 2019). Since the processing time has become a limitation for applicability at the household level, s~~Thermal composters are known for having a faster composting process; however, s~~ome modifications are still required to increase its efficiency and ensure its feasibility as a household composter.

This study developed an innovative household composter with several modifications which fill research gaps and addresses issues presented in previous studies. Furthermore, the composter designed here is simple to use, portable, and operated ~~using a smartphone~~automatically. Essentially, food waste was stirred, heated, mixed, and decomposed in the composter, allowing ~~mature and stable~~ active phase of composting to be ~~produced~~ obtained within a short period. The aim of the study was to demonstrate the utility of a thermal composter prototype in different operational environments. Furthermore, due to the limited research and the importance for further developing food waste management strategies at the household level, the goal of this study was to demonstrate a thermal composter that may accelerate the food waste composting process. The focus here was on compost quality and morphology, ammonia (NH_3) gas emissions, and the total operating cost.

2. METHODS

This research was conducted in the greenhouse of the Environmental Engineering Department, Faculty of Engineering, Diponegoro University. The thermal composter (see Fig.

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1) was made of stainless steel (Type 316 austenitic, Indonesia) with dimensions of 60 cm × 30 cm × 55 cm (length × width × height). The composter frame was made of corrosion-resistant galvalume, and its outer layer was made of white and green acrylic. The thermal composter consisted of an inlet chamber, a food waste chopper, a spiral stirrer driven by a motor (0.5 hp, 3-phase, 1370 rpm, China), and a heater (12 V). The heater was set to ~ 80 °C to accelerate the microbe metabolism and the humification rate ~~(Zhou et al., 2020)~~. The bottom and sides of the composter were equipped with insulators to reduce heat loss. Finally, activated carbon and a UV lamp were attached to the top of the composter to remove odors and microorganisms resulting from the food waste decomposition (Zhou et al., 2020)

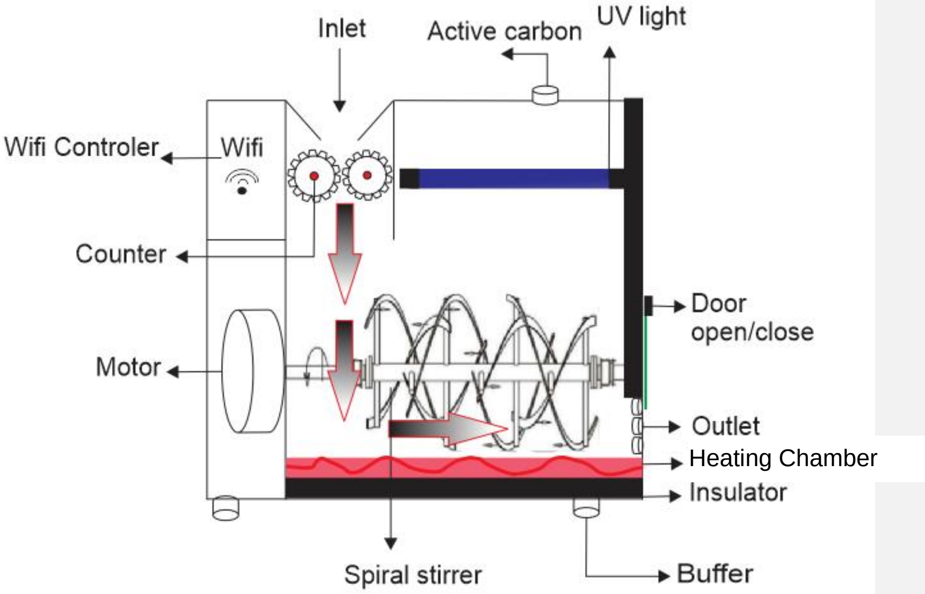

Fig. 1. Schematic diagram illustrating the design of the thermal composter developed ~~here~~in this study.

Food waste was collected from a restaurant in Semarang City using trash bags and transported to the Environmental Laboratory, Faculty of Engineering, Diponegoro University for analysis. Prior to starting the experiment, the composition and physical properties of the food waste were determined; thereafter, the food waste was mixed. The bulking agent used here came from mature and stable compost with a size of 100 mesh. The food waste consisted of various and mixed ingredients such as leftover rice, spinach, chayote, ~~and~~ banana peels, vegetable gravy, and many more. First, food waste (500 g per day) was added to the composter inlet and chopped until the food waste particle size was homogenized to ~ 2 cm. Thereafter, the bulking agent was added, accounting for as much as 30% (v/v) of the total food waste. The mixture was then periodically stirred by the spiral stirrer and slowly pushed into the heating chamber, where it was rotated for 1 min every 6 h. Despite the heater being set to 80 °C, the mixture's temperature gradually decreased to 28–30 °C while in the cooling compartment or outlet chamber. The composting cycle was carried out for 7 d by adjusting the rotational speed of the spiral stirrer to 80 rpm. ~~Mature c~~Compost was removed via the outlet chamber, with samples collected daily and stored at 4 °C until further analysis.

Laboratory tests were conducted to ensure that the compost was ~~mature and stable~~actively produced. Compost quality was assessed using the following parameters: (a) moisture content (MC), (b) electric conductivity (EC), (c) pH, (d) temperature, (e) total nitrogen (TN), and (f) total organic carbon (TOC). The gravimetric method was used to determine the MC, with the sample being heated to 105 °C using an oven (Memmert UN 50, Germany). The Kjeldahl method was used to determine TN, while TOC was assessed using the Walkley-Black method (UV-Vis 150 Spectrophotometer, Thermo Fisher Scientific, USA). The NH_3 emissions were assessed using the indophenol method and a spectrophotometer (Indonesia National Standard – SNI 19-7119.1-2005). The compost surface morphology was assessed using scanning electron microscopy (SEM) (Phenom ProX Desktop Scanning Electron Microscope, Thermo Fisher Scientific, USA) at a magnification of 100,000x. To do so, 2 g samples of three compost components (i.e., the bulking agent, food waste, and final compost) were collected and oven-dried at 110 °C for 48 h (Memmert, Germany). The sample was ground, sieved through 200 mesh and fixed on a stub (circular metallic plate holder). Thereafter, the sample was sputter coated with gold (Sputter Coater, Quorum Q300T D Plus, UK), ensuring visibility of the morphology.

Plant growth tests were conducted to assess the quality of the compost as a plant growth medium~~;~~. ~~this~~ This was done following the procedure described in Nguyen et al. (2020). Mung bean (*Vigna radiata*) plants sourced from a farm shop (Semarang, Indonesia) were planted in nine polybags of 5 cm × 15 cm (width × height) containing compost samples. All plants were treated equally and received the same daily watering. At 7 d, the plants were removed from the polybags, and several morphological parameters were measured, including height, weight, root length, and the number of leaves. The plant heights were measured using a ruler, plant weights were measured using an analytical balance (Mettler Toledo, Switzerland), and the germination rates were observed daily. The presence of flies and odors was recorded following the methodology described in Lleó et al. (2013). Finally, an economic evaluation was undertaken, aiming to assess the total costs incurred while operating the thermal composter. The total electrical power required for each component of the composter was converted into Indonesian Rupiah (IDR). Components that required electric power were the chopper, heater, spiral stirrer, and UV lamp. Replacement costs of the activated carbon and bulking agent were also calculated in detail. No labor or transportation costs were incurred.

3. RESULTS AND DISCUSSION

3.1. Moisture Content (MC)

The food waste contained an MC of 86.64% (Table 1); this was much higher than the recommended MC (i.e., 40–60%) for favorable microbial growth (Guidoni et al., 2018). However, food waste can produce a significant amount of gas and favors anaerobic processes, which in turn can produce foul odors and contribute to the emission of GHGs (Onwosi et al., 2017). The bulking agent contained an MC of 43.16% (Table 1). Despite this, during the composting process, the MC of the food waste and bulking agent mixture decreased drastically to 32.58% after 24 h (Table 1); this was due to the chopping, heating, and stirring that took place in the thermal composter. Water in the food waste evaporated during the heating and thermophilic composting process; this resulted in the MC decreasing to 19.76% at 4 d, while at 5 and 7 d, MCs increased to 23.55% and 23.89%, respectively (Table 1).

The microbes almost became inactive after the MC dropped below 20%; at this stage, the compost products could have been bagged (Zhou et al., 2020). The bulking agent, owing to its compression resistance, helped maintain the porosity and structure of the mixture during composting. Indeed, no leachate was observed, indicating that the addition of the bulking agent influenced the total amount of leachate formed during composting (Guidoni et al., 2018). Finally, the stirring frequency helped maintain the porosity of the mixture and added oxygen to the system.

Table 1. Compost quality parameters and growth test results.

Parameter	Units	FW	BA	C-1	C-2	C-3	C-4	C-5	C-6	C-7
MC	%	86.64	43.16	32.58	25.00	25.50	19.76	23.55	24.07	23.89
pH	-	6.63	6.70	6.72	6.32	6.49	6.53	6.72	6.27	7.01
EC	μScm^{-1}	1,591	3,270	~~0,~~891	1,148	1,124	1,435	960	1,170	1,179
Growth test										
Height	cm	0	7.~~,~~8	25.3	24.8	20.8	21.7	0	18.5	12.4
Weight	g	0	0.2403	0.4512	0.5116	0.4413	0.5308	0	0.5061	0.4843
Root length	cm	0	1.5	5.2	4.5	4.4	4.2	0	2.3	1
Leaf	single leaves	0	2	2	2	2	2	0	2	2

FW, food waste; BA, bulking agent; C-1–C-7, daily composting results (i.e., 7 d).

3.2. pH and Temperature

The food waste had an original pH of 6.63, while the bulking agent had a pH of 6.70 (Table 1). The daily addition of food waste did not significantly alter the mixture's pH, with the mixture at 1 and 7 d having pHs of 6.72 and 7.01, respectively. This pH range is ideal for developing bacteria and fungi, thus, contributing to the composting process in producing high-quality and mature compost. -Yuan & Zhu (2016) stated that the addition of a bulking agent accelerates the increase in pH. Typically, food waste that undergoes natural decomposition produces an acidic pH due to the formation of organic acid (Guidoni et al., 2018). The pH then begins to increase due to the ammonification of organic matter, where organic nitrogen is transformed into amide and ammoniacal nitrogen. The formation of NH_3, an alkaline reaction, also increases the pH. Zhou et al. (2020) found that processing food waste using a composter produced weakly acidic pHs during the initial and cooling stages, while an increase in pH was observed during the heating and thermophilic stages. Ultimately, the changes in pH may be attributable to pH imbalances caused by the microbial metabolic activity. Based on the pH value results, compost produced by the thermal composter could be taken during any of the seven composting process days and be used for agricultural purposes.

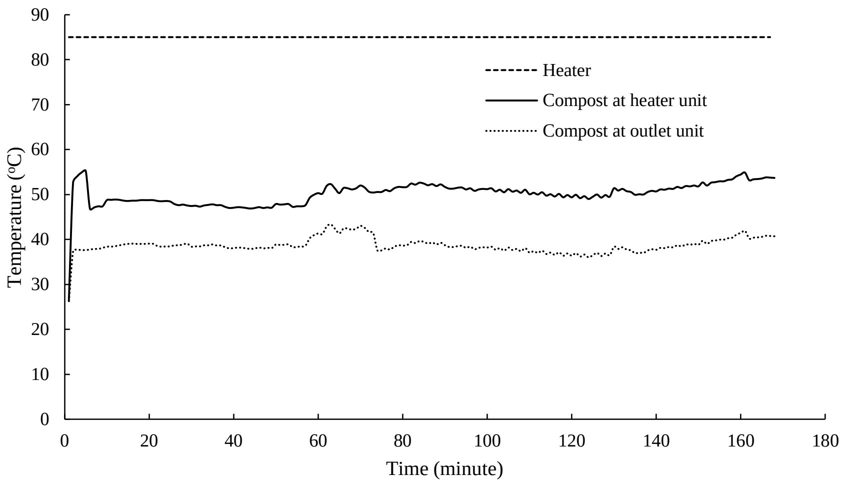

Fig. 2. Graph illustrating the temperature of the thermal composter heater (dashed line), as well as the compost temperature in the heating (solid line) and outlet chambers (dotted line).

The heater of the thermal composter was set to 80 °C, ensuring consistent thermophilic conditions in the heating chamber (Fig. 2). The composting temperature in the heating chamber rose rapidly from 26.3 °C to 52.63 °C within the first 20 min (Fig. 2). Within the same period, however, the composting temperature in the outlet chamber only rose from 26.3 °C to 37.44 °C (Fig. 2). A temperature of 52.63 °C in the heating chamber was beneficial for thermophilic microbial metabolism. At 7 d, the compost temperatures in the heating and outlet chambers were 53.69 °C and 40.69 °C, respectively (Fig. 2), indicating rapid food waste composting in the thermal composter. The thermophilic temperature positively impacts the decomposition rate of food waste so that the composting process can be completed in a day. In addition, this thermophilic temperature decreases food waste's water content, where the initial 86.64% food wastewater content decreases to 32.58% (day 1) and 23.89% (day 7).

3.3. Electric Conductivity (EC)

The original food waste and bulking agent EC values were 1,591 µScm^{-1} and 3,270 µScm^{-1}, respectively. The mixture had an EC value of 0.891 µScm^{-1} after being processed for 1 d in the thermal composter. The observed EC value decrease was due to the chopping, heating, and thermophilic decomposition that occurred in the thermal composter. However, the overall EC value during the composting process did not alter significantly and had a range of 1,148–1,179 µScm^{-1}. EC values reflect the salinity of the composting matrix (Onwosi et al., 2017). Furthermore, compost is safe for planting when it displays an EC value < 4,000 µScm^{-1}. In this study, EC values were consistently < 2,000 µScm^{-1} during the composting process, and thus, had no impact on biological activity (Mujtaba et al., 2021).

3.4. Flies and Odor

Flies typically land on food waste soon after its disposal. However, in this study, no flies were observed for 7 d, implying that the food waste and the products of its decomposition did not attract flies. Stirring of the mixture every 6 h did not affect the number of flies. A previous study found that the capacity of the composter was sufficient to stabilize the organic waste (Blazy et al., 2014). Guidoni et al. (2018) found that flies disappeared after the eleventh day of composting three treatments which varied in their ratio of rice husk to raw fruit and vegetables (i.e., 70:30, 50:50, 30:70; v:v). No strong odor was detected during this study. The bulking agent addition allowed the diffusion of gases and it maintained an aerobic composting process. In addition, bulking agents enhanced the inter-particle voids in the composite pile, thereby increasing the air permeability and regulating the humidity of the compost substrate (Yang et al., 2019).

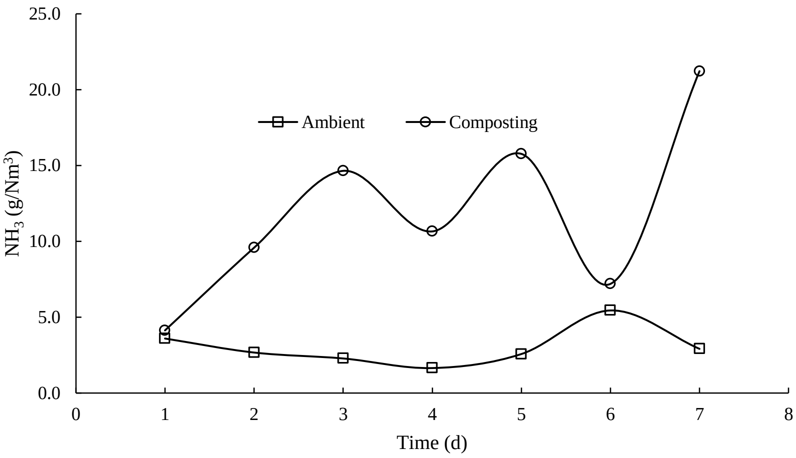

Fig. 3. Graph illustrating ammonia (NH_3) concentrations in ambient air (squares) and NH_3 emissions during seven days of composting using a thermal composter (circles).

3.5. NH_3 Emissions

Emission of NH_3 varies according to the substrate composition, particle sizes, moisture, oxygen distribution, initial temperature gradients, and the overall process conditions (Onwosi et al., 2017). The first day of the composting process produced an NH_3 emission of 4.1 g/Nm^3, with an increase to 9.6 g/Nm^3 occurring at 2 d (Fig. 3). This increase was likely due to the addition of food waste; moreover, the increasing trend continued until 7 d, which saw an NH_3 emission of 21.2 g/Nm^3 (Fig. 3). The NH_3 concentrations in ambient air ranged from 1.6–5.4 g/Nm^3, with the lowest concentration (i.e., 1.6 g/Nm^3) occurring at 4 d and the highest concentration (i.e., 5.4 g/Nm^3) at 6 d (Fig. 3). Overall, the NH_3 concentrations in ambient air did not change significantly ($p > 0.05$).

3.6. Total Organic Carbon (TOC)

Higher levels of TOC degradation indicate more stable compost (Sharma et al., 2017). After 1 d in the thermal composter, the TOC of the compost mixture decreased drastically by 75.94% ~~(Fig. 4)~~. The TOC for the remaining days ranged from 77.42–79.94%, lower than the initial TOC level (See Fig. 4). The decrease observed here supports Lalremruati & Devi (2021), who stated that the decomposition of vegetable waste is straightforward, owing to it mostly containing cellulose. Liu et al. (2018) reported a decrease in vegetable waste TOC ranging from 11.4–32.1%, when using sawdust, cow dung, and inoculum for 40 d. Notably, the TOC decrease observed in this study remained stable (i.e., 77.42–79.94%) throughout the 7-d period, despite the addition of 500 g of food waste per day (Fig. 4). Indeed, these results indicate that the thermal composter is effective in accelerating the degradation of TOC, owing to the integration of the mixing system, heating parameters, and bulking agent.

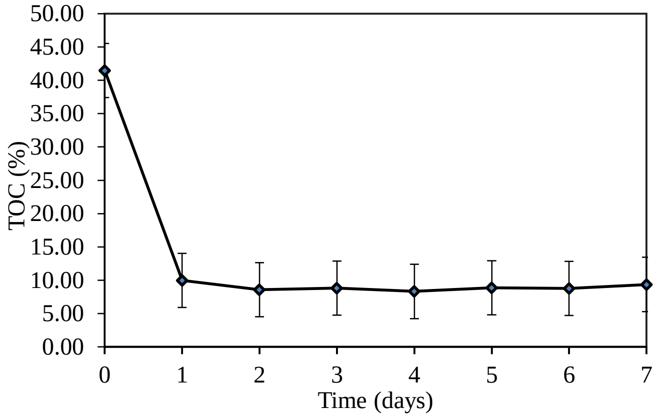

Fig. 4. Graph illustrating the level of total organic carbon (TOC) in food waste during seven days of composting using a thermal composter.

3.7. Total Nitrogen (TN)

The initial TN value decreased significantly at 2 and 3 d of the composting process. The decrease in TN is caused by the evaporation of ammonia, and lower pH results in less organic matter mineralization (Wang et al., 2017). As it may see in Fig. 3, the ammonia emission increased from 9.6 to 14.6 g/Nm^3. Therefore, the pH values for 2 and 3 d remain at 6.32 and 6.49, respectively, which are lesser than the pH at 1, 4, 5, and 7 d. ~~This decrease may have been caused by the high pH levels, which in turn can result in nitrogen loss due to volatilization.~~ Indeed, several studies have attributed the decrease in TN to the volatilization of NH_3, when temperature and pH were more than 45 °C ~~and 7.7, respectively~~ (Cáceres et al., 2018; Zhou et al., 2018). Nguyen et al. (2020) found that TN was influenced by temperature; in addition, the optimal TN was found in experiments that were rotated once per day and exhibited a C/N ratio of 20. Regarding the production of compost from domestic organic waste (Indonesia National Standard – SNI 19-7030-2004), the optimal TN for compost is a minimum of 0.40%. Indeed, the results obtained here confirm that the TN content in the compost collected at 1, 4, 6, and 7

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d meet this quality standard. The highest TN content (i.e., 0.49%) was found on the first day, while the lowest TN content (i.e., 0.28%), which does not meet the quality standard, was found at 3 d. Ultimately, temperature and the composition of the compost raw material can affect the TN in the compost.

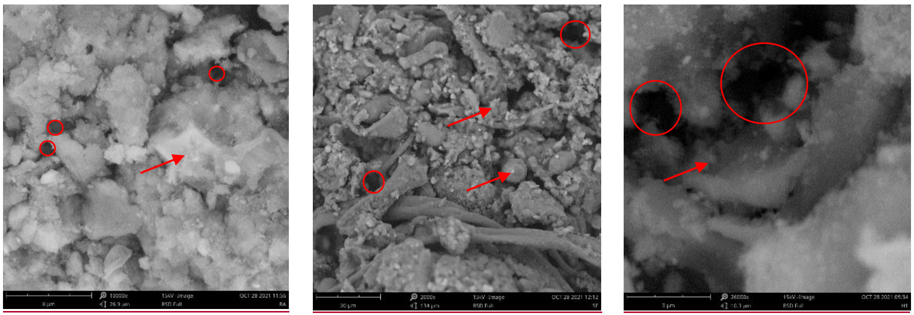
3.8. C/N Ratio

The C/N ratio is a conventional parameter used to assess the composting process (Zhou et al., 2018). The reduction of the C/N ratio due to the simultaneous consumption of carbon and nitrogen organic substrates indicates an effective composting process (Wang et al., 2016), with composts that display a C/N ratio < 20 being considered mature. According to the Ministry of Agriculture of Indonesia Number: 28/Permentan/SR.30/5/2009, organic and biological fertilizers, as well as soil enhancers, typically exhibit C/N ratios within the range of 15–25. The composting process in this study was 500 g of food waste being used as the initial compost raw material; on each of the ensuing days, an additional 500 g of food waste with a ~~different~~ typical composition was added. The results reveal that the food waste at 2, 3, and 5 d had C/N ratios > 25, ultimately displaying poor composting conditions; whereas at 1, 4, 6, and 7 d, the C/N ratios ranged from 20–25, indicating good compositions. The C/N ratio variation found in this study was ultimately driven by differences in the daily food waste composition and quantity.

3.9. SEM Images

SEM was used as an additional technique to assess micro-changes in the surface morphology of different compost components (See Fig. 5). In SEM, a focused high-energy electron beam is used to scan the surface of a specimen (Oñiguez et al., 2011). The resulting high-quality images provide information about the sample's external morphology (texture) and crystalline structure. Micrographs of food waste samples, compost, and the bulking agent (as

provided in supplementary materials) reveal different particle sizes and distributions per unit area, as well as heterogeneity in particle compaction. Moreover, micrographs showed that the compost sample exhibited larger pore diameters and had no particle compaction. However, while the initial food waste displayed small pore diameters, particle compaction was present. Biodegradation has been shown to lead to improved texture and particle compaction (Arora & Kaur, 2019). The same result was shown by Ajmal et al. (2021), where the food waste has tightened microscopic structure compared to the compost product. This result may be due to the microorganism activity, which reduces the particle size and increase the holes of the fermented food waste. Moreover, the surface roughness and irregular pore shapes shown in the compost product may indicate the possibility of microbial degradation during the composting process (Ma et al., 2022).



(a) (b) (c)

Fig. 5. Surface morphology of (a) bulking agent, (b) food waste, and (c) compost produced from thermal composter at 10,000x magnification. The red arrows indicate the distribution of particle sizes and the circles indicate the pore diameters.

3.10. Growth test

Compost products derived from food waste generally provide improved plant growth conditions. The plant growth tests revealed rapid and consistent daily mung bean growth. Growth tests using compost taken from six of the seven composting days (i.e., 1–4, 6, and 7 d) as well as the bulking agent alone, resulted in increased plant height and weight (Table 1). Growth tests using the fresh food waste alone, however, did not facilitate any plant growth (Table 1), with the waste beginning to rot at 1 d. Moreover, no plant growth was observed t 5 d (Table 1); this was due to the accumulation of acidic decomposition products. Ultimately, the results presented here agree with the literature that compost from food waste can be used as a ~~quality~~ plant growth medium (Nguyen et al., 2020).

3.11. ~~Economic~~ Practical Evaluation and Future Research Direction

Household food waste composting does not require labor, transport, sorting, or processing fees. Zhou et al. (2020) believe that the in-situ composting system differs from the centralized composting system. The thermal composter used in this study processed 1 kg of food waste per day, using a total electrical power of 1.~~,~~452 kWh~~ (Fig. 5)~~. This total power consists of the shredding unit (i.e., 0.00375 kWh), the spiral stirring unit (i.e., 0.00828 kWh), and the heating unit (i.e., 1.440 kWh). To process 1 kg of food waste in a day, the heating unit required the most power as it operated for 24 h, while the shredding and stirring units operated for only 30 and 80 s, respectively. The total cost for operating the thermal composter amounted to 2,097.76 IDR to process 1 kg of food waste in a single day. The total cost of the composter developed by Zhou et al. (2020) requires \$0.033 (445.98 IDR) per kg for food waste, but the composting time is longer (four days). Even though the electricity cost is 2,097.76 IDR to process 1 kg of food waste in a day, food waste composting using a thermal composter still get profits from selling the compost product as a fertilizer for 5,000.00 IDR (Paduloh & Rosihan, 2021). ~~The compost produced from the thermal composter can be used directly as fertilizer,~~

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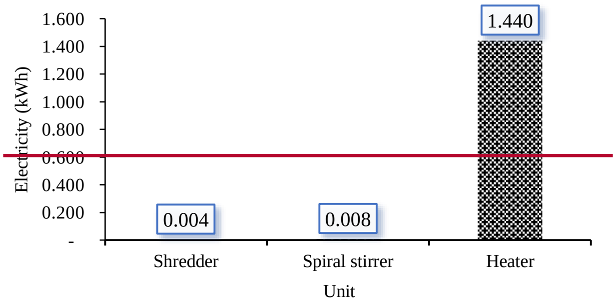
~~while household food waste can be reduced.~~ Moreover, the compost improves soil quality, assists the remediation of contaminated soil and reduces the need for chemical fertilizers. Solar cells can be an alternative AC power source for thermal composter operations. In addition, it is necessary to increase public acceptance of the thermal composter so that they can use it to treat food waste.



~~**Fig. 5.** Graph illustrating the electrical power required by the thermal composter developed here, to process 1 kg of food waste in a day.~~

4. CONCLUSION

Thermal composting is considered a straightforward and effective strategy to manage household food waste. In this study, an innovative household thermal composter was developed and its feasibility assessed. ~~Mature and stable~~ Active phase of composting was ~~obtained~~ finished after ~~only~~ a single day of treatment, with MC, pH, temperature, EC, TOC, TN, C/N ratios, and SEM images meeting the criteria required for high quality compost. Regardless, the compost obtained after a single day was used successfully as a plant growth medium, confirming the compost's low toxicity level. Furthermore, the composter was shown to require a small amount of daily electricity to process food waste.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest exists.

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An innovative thermal composter to accelerate food waste decomposition at the household level

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ABSTRACT

An innovative, portable thermal composter was developed to accelerate the decomposition of food waste at household. The study aimed to evaluate the performance of the composter by assessing the quality of the compost produced. Food waste was chopped, mixed, stirred at 80 rpm, and heated to ~55 °C; thereafter, a bulking agent and stimulated microorganisms were added to the mixture. The composter mixing speed was assessed to calculate the feasible composting time. The results revealed that the active phase of composting process could be completed in a day, producing good quality compost. The pH, electric conductivity, and C/N ratio of the compost was 6.72, 1148–1179 μScm^{-1}, and 20.38, respectively. The lowest ammonia emissions (i.e., 7.2 g/Nm^3) were produced on the sixth day. The total cost required to process 1 kg of food waste in a day was only 2097.76 Indonesian Rupiah (IDR), highlighting the feasibility of this technology.

1. Introduction

Nearly a third of the worldwide food production for human consumption is lost or wasted, accounting for 1.3 billion tons of food per year. The high generation of food waste, representing a global economic loss, which is accounting around $400 billion per year (Raj et al., 2022). Among various other types of waste, food waste may generate the highest greenhouse gas (GHG) emissions, as it produces an enormous number of contaminants through natural microbial degradation and other indirect processes, including transportation and the use of food processing machinery (Shen et al., 2020). Therefore, preventing food waste at the household level, downstream of the food supply chain, is critical in limiting climate change (Parfitt et al., 2010).

There are several food waste management strategies, including composting (Cesaro et al., 2019), animal feed (Mo et al., 2018), anaerobic/aerobic digestion (Wainaina et al., 2020), gasification, incineration (You et al., 2016), pyrolysis (Kim et al., 2020), and direct landfill disposal (Goodman-Smith et al., 2020). Composting remains the most widespread solution in developing countries, where it treats ~90–96 % of food waste (Thi et al., 2015). Effective food waste management has been proven to reduce pollutants, odors, and GHG emissions (Wei et al., 2017; Zaman et al., 2021). In addition, composting is a common practice that can be easily implemented in residential households.

Composting systems at the household and community level have been discussed by Lu and Sidortsov (2019). Household-level composting equipment allows residents to compost their food waste, ultimately reducing the volume of domestic waste transported to communal waste processing facilities. There are, however, some challenges facing composting systems at the household level. For example, there is the likelihood of odor emissions during the biodegradation process (Zhou et al., 2020). Moreover, the long processing times involved with composting may lead to residents being unwilling to compost in their homes. The success of household-level composting also depends on the knowledge, capacity, and self-awareness of the residents who manage the household's waste (Fadhullah et al., 2022).

There are some techniques presented in previous literatures for reducing the processing time of household composting. For instance, Kalamdhad et al. (2009) created a drum-shaped thermophilic composter consisting of chambers with varying temperatures at its chamber. The thermophilic conditions allow for microbial metabolism activation, accelerating the humification rate. The higher the temperature, the greater the microbiological activity will be (Ottani et al., 2022). Food

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waste composting with the addition of microorganisms and thermal elements (0–100 °C) reached the maximum temperature faster (3 days), and the maturation period decreased (4 weeks) (Charkhestani and Kebria, 2022). The composting time of 4 weeks is still contrary to the community's wishes, where they want the composting process to happen right after they throw the waste away in the composting machine. Awasthi et al. (2017) also found that adding multifunctional microorganisms produced better germination test results and a composting period of 20 days. A recent study reveals that adding biochar can increase the composting temperature and achieve an advanced thermophilic temperature in a short period of time. Thus, making the composting time lasted for only 20 days (Jain et al., 2018). Oktiawan et al. (2018) used a bulking agent at as much as 30 % of the total waste to produce mature and stable compost. A processed food waste size of ±2 mm is ideal for microbes to carry out the humification process and increase composting efficiency. Therefore, continuous aeration and rotation can also reduce the active phase of composting treatment from several weeks to only 4.5 days (Alkoaik, 2019). Since the processing time has become a limitation for applicability at the household level, some modifications are still required to increase its efficiency and ensure its feasibility as a household composter.

This study developed an innovative household composter with several modifications which fill research gaps and addresses issues presented in previous studies. Furthermore, the composter designed here is simple to use, portable, and operated automatically. Essentially, food waste was stirred, heated, mixed, and decomposed in the composter, allowing active phase of composting to be obtained within a short period. The aim of the study was to demonstrate the utility of a thermal composter prototype in different operational environments. Furthermore, due to the limited research and the importance for further developing food waste management strategies at the household level, the goal of this study was to demonstrate a thermal composter that may accelerate the food waste composting process. The focus here was on compost quality and morphology, ammonia (NH_3) gas emissions, and the total operating cost.

2. Methods

This research was conducted in the greenhouse of the Environmental Engineering Department, Faculty of Engineering, Diponegoro University. The thermal composter (see Fig. 1) was made of stainless steel (Type 316 austenitic, Indonesia) with dimensions of 60 cm × 30 cm × 55 cm (length × width × height). The composter frame was made of corrosion-resistant galvalume, and its outer layer was made of white and green acrylic. The thermal composter consisted of an inlet chamber, a food waste chopper, a spiral stirrer driven by a motor (0.5 hp, 3-phase,

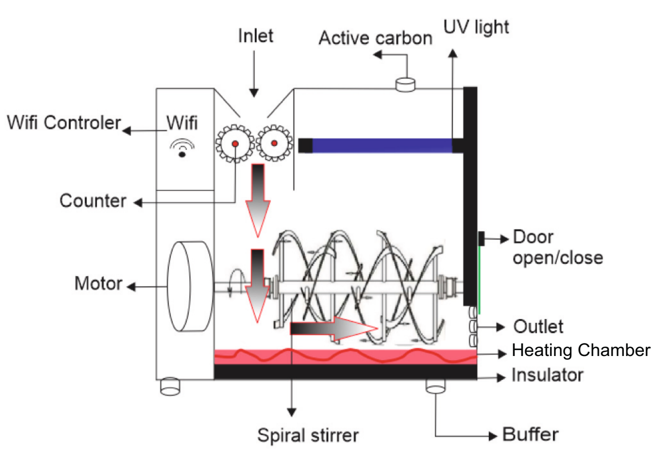


Fig. 1. Schematic diagram illustrating the design of the thermal composter developed in this study.

1370 rpm, China), and a heater (12 V). The heater was set to ~80 °C to accelerate the microbe metabolism and the humification rate. The bottom and sides of the composter were equipped with insulators to reduce heat loss. Finally, activated carbon and a UV lamp were attached to the top of the composter to remove odors and microorganisms resulting from the food waste decomposition (Zhou et al., 2020).

Food waste was collected from a restaurant in Semarang City using trash bags and transported to the Environmental Laboratory, Faculty of Engineering, Diponegoro University for analysis. Prior to starting the experiment, the composition and physical properties of the food waste were determined; thereafter, the food waste was mixed. The bulking agent used here came from mature and stable compost with a size of 100 mesh. The food waste consisted of various and mixed ingredients such as leftover rice, spinach, chayote, banana peels, vegetable gravy, and many more. First, food waste (500 g per day) was added to the composter inlet and chopped until the food waste particle size was homogenized to ~2 cm. Thereafter, the bulking agent was added, accounting for as much as 30 % (v/v) of the total food waste. The mixture was then periodically stirred by the spiral stirrer and slowly pushed into the heating chamber, where it was rotated for 1 min every 6 h. Despite the heater being set to 80 °C, the mixture's temperature gradually decreased to 28–30 °C while in the cooling compartment or outlet chamber. The composting cycle was carried out for 7 d by adjusting the rotational speed of the spiral stirrer to 80 rpm. Compost was removed via the outlet chamber, with samples collected daily and stored at 4 °C until further analysis.

Laboratory tests were conducted to ensure that the compost was actively produced. Compost quality was assessed using the following parameters: (a) moisture content (MC), (b) electric conductivity (EC), (c) pH, (d) temperature, (e) total nitrogen (TN), and (f) total organic carbon (TOC). The gravimetric method was used to determine the MC, with the sample being heated to 105 °C using an oven (Memmert UN 50, Germany). The Kjeldahl method was used to determine TN, while TOC was assessed using the Walkley-Black method (UV–Vis 150 Spectrophotometer, Thermo Fisher Scientific, USA). The NH_3 emissions were assessed using the indophenol method and a spectrophotometer (Indonesia National Standard – SNI 19-7119.1-2005). The compost surface morphology was assessed using scanning electron microscopy (SEM) (Phenom ProX Desktop Scanning Electron Microscope, Thermo Fisher Scientific, USA) at a magnification of 100,000×. To do so, 2 g samples of three compost components (i.e., the bulking agent, food waste, and final compost) were collected and oven-dried at 110 °C for 48 h (Memmert, Germany). The sample was ground, sieved through 200 mesh and fixed on a stub (circular metallic plate holder). Thereafter, the sample was sputter coated with gold (Sputter Coater, Quorum Q300T D Plus, UK), ensuring visibility of the morphology.

Plant growth tests were conducted to assess the quality of the compost as a plant growth medium. This was done following the procedure described in Nguyen et al. (2020). Mung bean (*Vigna radiata*) plants sourced from a farm shop (Semarang, Indonesia) were planted in nine polybags of 5 cm × 15 cm (width × height) containing compost samples. All plants were treated equally and received the same daily watering. At 7 d, the plants were removed from the polybags, and several morphological parameters were measured, including height, weight, root length, and the number of leaves. The plant heights were measured using a ruler, plant weights were measured using an analytical balance (Mettler Toledo, Switzerland), and the germination rates were observed daily. The presence of flies and odors was recorded following the methodology described in Lleó et al. (2013). Finally, an economic evaluation was undertaken, aiming to assess the total costs incurred while operating the thermal composter. The total electrical power required for each component of the composter was converted into Indonesian Rupiah (IDR). Components that required electric power were the chopper, heater, spiral stirrer, and UV lamp. Replacement costs of the activated carbon and bulking agent were also calculated in detail. No labor or transportation costs were incurred.

3. Results and discussion

3.1. Moisture content (MC)

The food waste contained an MC of 86.64 % (Table 1); this was much higher than the recommended MC (i.e., 40–60 %) for favorable microbial growth (Guidoni et al., 2018). However, food waste can produce a significant amount of gas and favors anaerobic processes, which in turn can produce foul odors and contribute to the emission of GHGs (Onwosi et al., 2017). The bulking agent contained an MC of 43.16 % (Table 1). Despite this, during the composting process, the MC of the food waste and bulking agent mixture decreased drastically to 32.58 % after 24 h (Table 1); this was due to the chopping, heating, and stirring that took place in the thermal composter. Water in the food waste evaporated during the heating and thermophilic composting process; this resulted in the MC decreasing to 19.76 % at 4 d, while at 5 and 7 d, MCs increased to 23.55 % and 23.89 %, respectively (Table 1).

The microbes almost became inactive after the MC dropped below 20 %; at this stage, the compost products could have been bagged (Zhou et al., 2020). The bulking agent, owing to its compression resistance, helped maintain the porosity and structure of the mixture during composting. Indeed, no leachate was observed, indicating that the addition of the bulking agent influenced the total amount of leachate formed during composting (Guidoni et al., 2018). Finally, the stirring frequency helped maintain the porosity of the mixture and added oxygen to the system.

3.2. pH and temperature

The food waste had an original pH of 6.63, while the bulking agent had a pH of 6.70 (Table 1). The daily addition of food waste did not significantly alter the mixture's pH, with the mixture at 1 and 7 d having pHs of 6.72 and 7.01, respectively. This pH range is ideal for developing bacteria and fungi, thus, contributing to the composting process in producing high-quality and mature compost. Yuan and Zhu (2016) stated that the addition of a bulking agent accelerates the increase in pH. Typically, food waste that undergoes natural decomposition produces an acidic pH due to the formation of organic acid (Guidoni et al., 2018). The pH then begins to increase due to the ammonification of organic matter, where organic nitrogen is transformed into amide and ammoniacal nitrogen. The formation of NH_3, an alkaline reaction, also increases the pH. Zhou et al. (2020) found that processing food waste using a composter produced weakly acidic pHs during the initial and cooling stages, while an increase in pH was observed during the heating and thermophilic stages. Ultimately, the changes in pH may be attributable to pH imbalances caused by the microbial metabolic activity. Based on the pH value results, compost produced by the thermal composter could be taken during any of the seven composting process days and be used for agricultural purposes.

The heater of the thermal composter was set to 80 °C, ensuring consistent thermophilic conditions in the heating chamber (Fig. 2). The composting temperature in the heating chamber rose rapidly from 26.3 °C to 52.63 °C within the first 20 min (Fig. 2). Within the same period, however, the composting temperature in the outlet chamber only rose from 26.3 °C to 37.44 °C (Fig. 2). A temperature of 52.63 °C in the heating chamber was beneficial for thermophilic microbial metabolism. At 7 d, the compost temperatures in the heating and outlet chambers were 53.69 °C and 40.69 °C, respectively (Fig. 2), indicating rapid food waste composting in the thermal composter. The thermophilic temperature positively impacts the decomposition rate of food waste so that the composting process can be completed in a day. In addition, this thermophilic temperature decreases food waste's water content, where the initial 86.64 % food wastewater content decreases to 32.58 % (day 1) and 23.89 % (day 7).

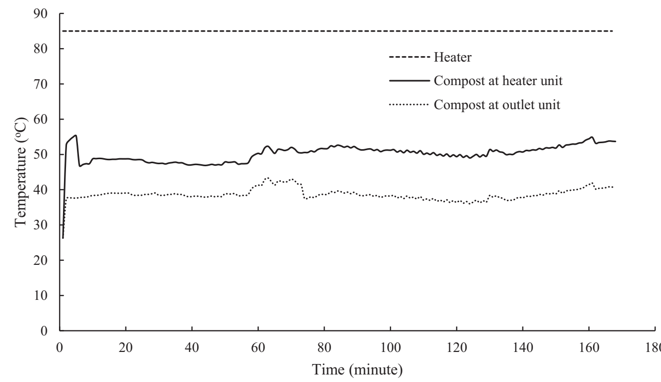


Fig. 2. Graph illustrating the temperature of the thermal composter heater (dashed line), as well as the compost temperature in the heating (solid line) and outlet chambers (dotted line).

3.3. Electric conductivity (EC)

The original food waste and bulking agent EC values were 1591 μScm^{-1} and 3270 μScm^{-1}, respectively. The mixture had an EC value of 0.891 μScm^{-1} after being processed for 1 d in the thermal composter. The observed EC value decrease was due to the chopping, heating, and thermophilic decomposition that occurred in the thermal composter. However, the overall EC value during the composting process did not alter significantly and had a range of 1148–1179 μScm^{-1}. EC values reflect the salinity of the composting matrix (Onwosi et al., 2017). Furthermore, compost is safe for planting when it displays an EC value <4000 μScm^{-1}. In this study, EC values were consistently <2000 μScm^{-1} during the composting process, and thus, had no impact on biological activity (Mujtaba et al., 2021).

3.4. Flies and odor

Flies typically land on food waste soon after its disposal. However, in this study, no flies were observed for 7 d, implying that the food waste and the products of its decomposition did not attract flies. Stirring of the

Table 1
Compost quality parameters and growth test results.

Parameter	Units	FW	BA	C-1	C-2	C-3	C-4	C-5	C-6	C-7
MC	%	86.64	43.16	32.58	25.00	25.50	19.76	23.55	24.07	23.89
pH	–	6.63	6.70	6.72	6.32	6.49	6.53	6.72	6.27	7.01
EC	μScm^{-1}	1591	3270	891	1148	1124	1435	960	1170	1179
Growth test										
Height	cm	0	7.8	25.3	24.8	20.8	21.7	0	18.5	12.4
Weight	g	0	0.2403	0.4512	0.5116	0.4413	0.5308	0	0.5061	0.4843
Root length	cm	0	1.5	5.2	4.5	4.4	4.2	0	2.3	1
Leaf	Single leaves	0	2	2	2	2	2	0	2	2

FW, food waste; BA, bulking agent; C-1–C-7, daily composting results (i.e., 7 d).

mixture every 6 h did not affect the number of flies. A previous study found that the capacity of the composter was sufficient to stabilize the organic waste (Blazy et al., 2014). Guidoni et al. (2018) found that flies disappeared after the eleventh day of composting three treatments which varied in their ratio of rice husk to raw fruit and vegetables (i.e., 70:30, 50:50, 30:70; v:v). No strong odor was detected during this study. The bulking agent addition allowed the diffusion of gases and it maintained an aerobic composting process. In addition, bulking agents enhanced the inter-particle voids in the composite pile, thereby increasing the air permeability and regulating the humidity of the compost substrate (Yang et al., 2019).

3.5. NH_3 emissions

Emission of NH_3 varies according to the substrate composition, particle sizes, moisture, oxygen distribution, initial temperature gradients, and the overall process conditions (Onwosi et al., 2017). The first day of the composting process produced an NH_3 emission of 4.1 g/Nm^3, with an increase to 9.6 g/Nm^3 occurring at 2 d (Fig. 3). This increase was likely due to the addition of food waste; moreover, the increasing trend continued until 7 d, which saw an NH_3 emission of 21.2 g/Nm^3 (Fig. 3). The NH_3 concentrations in ambient air ranged from 1.6 to 5.4 g/Nm^3, with the lowest concentration (i.e., 1.6 g/Nm^3) occurring at 4 d and the highest concentration (i.e., 5.4 g/Nm^3) at 6 d (Fig. 3). Overall, the NH_3 concentrations in ambient air did not change significantly ($p > 0.05$).

3.6. Total organic carbon (TOC)

Higher levels of TOC degradation indicate more stable compost (Sharma et al., 2017). After 1 d in the thermal composter, the TOC of the compost mixture decreased drastically by 75.94 %. The TOC for the remaining days ranged from 77.42 to 79.94 %, lower than the initial TOC level (see Fig. 4). The decrease observed here supports Lalremruati and Devi (2021), who stated that the decomposition of vegetable waste is straightforward, owing to it mostly containing cellulose. Liu et al. (2018) reported a decrease in vegetable waste TOC ranging from 11.4 to 32.1 %, when using sawdust, cow dung, and inoculum for 40 d. Notably, the TOC decrease observed in this study remained stable (i.e., 77.42–79.94 %) throughout the 7-d period, despite the addition of 500 g of food waste per day (Fig. 4). Indeed, these results indicate that the thermal composter is effective in accelerating the degradation of TOC, owing to the integration of the mixing system, heating parameters, and bulking agent.

3.7. Total nitrogen (TN)

The initial TN value decreased significantly at 2 and 3 d of the

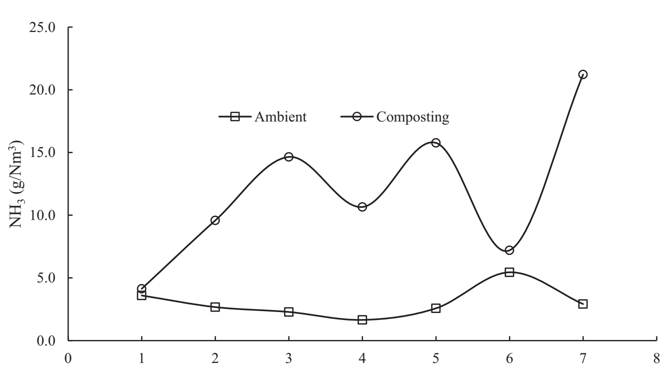


Fig. 3. Graph illustrating ammonia (NH_3) concentrations in ambient air (squares) and NH_3 emissions during seven days of composting using a thermal composter (circles).

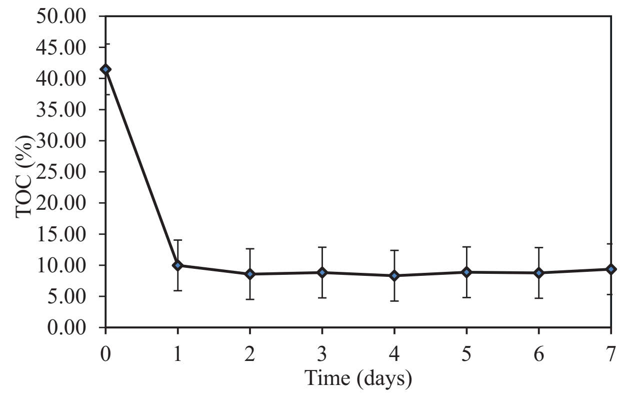


Fig. 4. Graph illustrating the level of total organic carbon (TOC) in food waste during seven days of composting using a thermal composter.

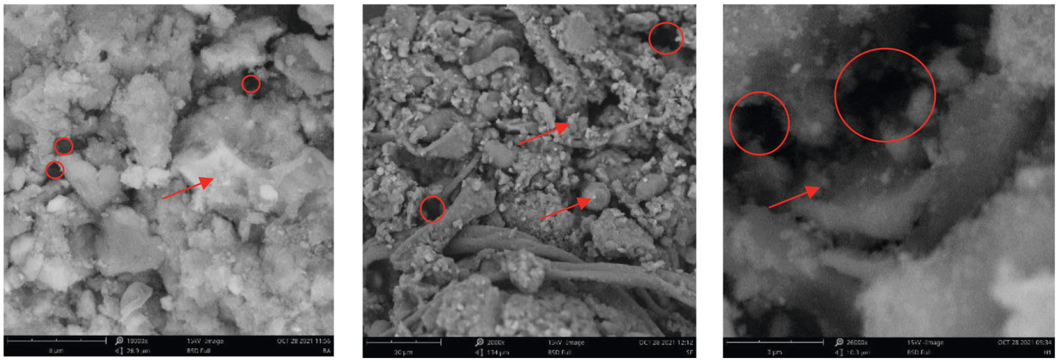
composting process. The decrease in TN is caused by the evaporation of ammonia, and lower pH results in less organic matter mineralization (Wang et al., 2017). As it may see in Fig. 3, the ammonia emission increased from 9.6 to 14.6 g/Nm^3. Therefore, the pH values for 2 and 3 d remain at 6.32 and 6.49, respectively, which are lesser than the pH at 1, 4, 5, and 7 d. Indeed, several studies have attributed the decrease in TN to the volatilization of NH_3, when temperature and pH were >45 °C (Cáceres et al., 2018; Zhou et al., 2018). Nguyen et al. (2020) found that TN was influenced by temperature; in addition, the optimal TN was found in experiments that were rotated once per day and exhibited a C/N ratio of 20. Regarding the production of compost from domestic organic waste (Indonesia National Standard – SNI 19-7030-2004), the optimal TN for compost is a minimum of 0.40 %. Indeed, the results obtained here confirm that the TN content in the compost collected at 1, 4, 6, and 7 d meet this quality standard. The highest TN content (i.e., 0.49 %) was found on the first day, while the lowest TN content (i.e., 0.28 %), which does not meet the quality standard, was found at 3 d. Ultimately, temperature and the composition of the compost raw material can affect the TN in the compost.

3.8. C/N ratio

The C/N ratio is a conventional parameter used to assess the composting process (Zhou et al., 2018). The reduction of the C/N ratio due to the simultaneous consumption of carbon and nitrogen organic substrates indicates an effective composting process (Wang et al., 2016), with composts that display a C/N ratio < 20 being considered mature. According to the Ministry of Agriculture of Indonesia Number: 28/Permentan/SR.30/5/2009, organic and biological fertilizers, as well as soil enhancers, typically exhibit C/N ratios within the range of 15–25. The composting process in this study was 500 g of food waste being used as the initial compost raw material; on each of the ensuing days, an additional 500 g of food waste with a typical composition was added. The results reveal that the food waste at 2, 3, and 5 d had C/N ratios >25, ultimately displaying poor composting conditions; whereas at 1, 4, 6, and 7 d, the C/N ratios ranged from 20 to 25, indicating good compositions. The C/N ratio variation found in this study was ultimately driven by differences in the daily food waste composition and quantity.

3.9. SEM images

SEM was used as an additional technique to assess micro-changes in the surface morphology of different compost components (see Fig. 5). In SEM, a focused high-energy electron beam is used to scan the surface of a specimen (Oñiguez et al., 2011). The resulting high-quality images provide information about the sample's external morphology (texture) and crystalline structure. Micrographs of food waste samples, compost,



(a) (b) (c)

Fig. 5. Surface morphology of (a) bulking agent, (b) food waste, and (c) compost produced from thermal composter at 10,000× magnification. The red arrows indicate the distribution of particle sizes and the circles indicate the pore diameters. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and the bulking agent as provided in Fig. 5 reveal different particle sizes and distributions per unit area, as well as heterogeneity in particle compaction. Moreover, micrographs showed that the compost sample exhibited larger pore diameters and had no particle compaction. However, while the initial food waste displayed small pore diameters, particle compaction was present. Biodegradation has been shown to lead to improved texture and particle compaction (Arora and Kaur, 2019). The same result was shown by Ajmal et al. (2021), where the food waste has tightened microscopic structure compared to the compost product. This result may be due to the microorganism activity, which reduces the particle size and increase the holes of the fermented food waste. Moreover, the surface roughness and irregular pore shapes shown in the compost product may indicate the possibility of microbial degradation during the composting process (Ma et al., 2022).

3.10. Growth test

Compost products derived from food waste generally provide improved plant growth conditions. The plant growth tests revealed rapid and consistent daily mung bean growth. Growth tests using compost taken from six of the seven composting days (i.e., 1–4, 6, and 7 d) as well as the bulking agent alone, resulted in increased plant height and weight (Table 1). Growth tests using the fresh food waste alone, however, did not facilitate any plant growth, with the waste beginning to rot at 1 d. Moreover, no plant growth was observed t 5 d; this was due to the accumulation of acidic decomposition products. Ultimately, the results presented here agree with the literature that compost from food waste can be used as a plant growth medium (Nguyen et al., 2020).

3.11. Practical evaluation and future research direction

Household food waste composting does not require labor, transport, sorting, or processing fees. Zhou et al. (2020) believe that the in-situ composting system differs from the centralized composting system. The thermal composter used in this study processed 1 kg of food waste per day, using a total electrical power of 1.452 kWh. This total power consists of the shredding unit (i.e., 0.00375 kWh), the spiral stirring unit (i.e., 0.00828 kWh), and the heating unit (i.e., 1.440 kWh). To process 1 kg of food waste in a day, the heating unit required the most power as it operated for 24 h, while the shredding and stirring units operated for only 30 and 80 s, respectively. The total cost for operating the thermal composter amounted to 2097.76 IDR to process 1 kg of food waste in a single day. The total cost of the composter developed by Zhou et al. (2020) requires \$0.033 (445.98 IDR) per kg for food waste, but the composting time is longer (four days). Even though the electricity cost is 2097.76 IDR to process 1 kg of food waste in a day, food waste composting using a thermal composter still get profits from selling the compost product as a fertilizer for 5000.00 IDR (Paduloh et al., 2022). Moreover, the compost improves soil quality, assists the remediation of contaminated soil and reduces the need for chemical fertilizers. Solar cells can be an alternative AC power source for thermal composter operations. In addition, it is necessary to increase public acceptance of the thermal composter so that they can use it to treat food waste.

4. Conclusion

Thermal composting is considered a straightforward and effective strategy to manage household food waste. In this study, an innovative household thermal composter was developed and its feasibility assessed. Active phase of composting was finished after a single day of treatment, with MC, pH, temperature, EC, TOC, TN, C/N ratios, and SEM images meeting the criteria required for high quality compost. Regardless, the compost obtained after a single day was used successfully as a plant growth medium, confirming the compost's low toxicity level. Furthermore, the composter was shown to require a small amount of daily electricity to process food waste.

CRediT authorship contribution statement

Badrus Zaman: Conceptualization, Supervision, Writing – review & editing. **Nurandani Hardyanti:** Validation, Resources, Software. **Purwono:** Investigation, Formal analysis, Project administration. **Bimastyaji Surya Ramadan:** Writing – review & editing, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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